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Differences in litter size and growth rate among purebred and crossbred swine

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DIFFERENCES IN LITTER SIZE AND GROWTH RATE AMONG PUREBRED AND CROSSBRED SWINE

by

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TABLE OF CONTENTS

I. INTRODUCTION

Improvement of swine through breeding has been achieved largely through developing and maintaining many herds of purebred swine. These herds have provided a source of purebred boars for use by farmers in producing market hogs. The various breeds are used in purebreeding, grading-up toward a breed, and outbreeding to produce market hogs. The latter use, outbreeding to produce market hogs, is the topic of this study. Matings considered ranged in diversity from those made between inbred lines within a breed to those made using a purebred boar on a sow that was a combination of four breeds, all different from the breed of the boar.

Numerous experiments were conducted by experiment stations between 1890 and 1925 in which litters by purebred boars were compared with litters by non-purebred boars. Generally the comparisons were in favor of purebred boars. Following this many experiment stations and hog producers compared crossbred litters with purebred litters for market hog production. The results usually were in favor of the crosses but in most cases the differences were small.

Outbreeding is the general scientific term for mating animals distinctly less closely related to each other than the average of the population concerned. In recent years systems of outcrossing have been advanced and tested experimentally. The maximum practical usefulness of these systems seems to lie in the production of market animals. "Criss-crossing" of two breeds in rotation, and rotation of three or more breeds (concerned in this study) have brought out not only differences in favor of first-cross litters but also advantages gained by use of crossbred sows as compared with pedigreed sows, both being bred to purebred boars.

The most recent method of breeding swine to be investigated experimentally is that of topcrossing. Inbred boars of several different lines and noninbred boars were used in topcrosses on similar groups of sows. Litters by inbred boars excelled those by noninbred boars in 154-day weight. Then topcross and nontopcross gilts were compared, and an over-all difference was found in favor of gilts by the inbred boars, which amounted to a little more than one pig per litter at farrowing and weaning, and about 37 pounds in weight of litters weaned.

Trials are in progress at some stations in which inbred boars of different lines are used in rotation to produce "rotation line crosses".

Over the past ten years, the Iowa Agricultural Experiment Station has carried out extensive inbreeding and outbreeding programs with swine in order to expand the knowledge about breeding systems in general and also to answer questions pertaining to specific breeds and crosses and reciprocal crosses.

The production of cross-line and crossbred pigs used in this study had several purposes, namely,

1. To compare the performance of purebred (cross-line) pigs with that of crossbred pigs.

2. To compare purebred, first cross, second cross, and third cross sows in order to measure the amount of heterosis.

3. To compare reciprocal crosses in order to determine the presence or absence of maternal effects.

4. To obtain information concerning the relative value of certain inbred lines of Poland China boars when crossed on Landrace sows.

5. To examine relative performance of the Beltsville strains, the Yorkshire and Hampshire breeds when used as boars for crossbreeding on a uniform sample of sows.

6. As the experiments progressed, facilities became available to do more testing. It was of interest to determine whether the farmer practicing crossbreeding in his swine herd should breed his second cross sows back to a previous breed (three breed rotation) or continue with a fourth or fifth breed.

7. Poland-Landrace crossbred sows have become widely regarded as good sows to use in a crossbreeding program. Duroc and Chester White boars were compared in matings with these sows.

8. Estimates of the components of variance due to boars, sows, boar x sow interaction and error were made in order to determine importance of these sources of variation.

II. REVIEW OF LITERATURE

As early as 1904 Otis (1904) at the Kansas Station reported "that the crossbreds made the best gains and at less cost for feed consumed".

"It has been the general experience of stock breeders that the first cross between two pure breeds is superior in vigor and quickness of growth to either parent breed." Sewall Wright (1919).

Wright (1922) reported on the effects of inbreeding and crossbreeding in guinea pigs. He compared animals in inbred lines; single, three-way, and double-crosses; and randombred stock. His conclusions included the following: crosses between different inbred families resulted in a marked improvement over both parental stocks in every respect, after correcting for the effects of size of litter on other characters. In the case of adult weight, maximum improvement appeared in progeny of the first cross. Mortality between birth and weaning decreased about 11% in the first cross, but there was some additional advance in the progeny from crossbred dams mated with an unrelated male. In weight at 33 days, first cross progeny showed a 9% improvement and progeny from crossline females showed an additional 4% improvement. Size of litter was increased over 10% when both sire and dam were crossbred, but none at all in first-cross progeny. The base point in each of the above comparisons was the average of the inbred lines. Double-cross progeny and progeny from mating inbred males to crossbred females equalled or exceeded the randombred stock in average size of litter, but only the double-cross progeny exceeded the randombred stock in individual weight at 33 days, which was weaning age. In most of the traits studied, the double cross progeny were superior to those from any other type of mating.

Davidson (1926) pointed out that in Denmark the cross-breds matured earlier than either the Landrace or Large White swine.

Duckham (1926) concluded from his study of Danish swine that crossbreeding results in low mortality during suckling, high average daily gains, and less feed per pound gain.

McKenzie (1928) found considerable difference in the average birth weights of pigs farrowed in litters of different size but there was no regular trend relating litter size to the weight of the pigs. In the data he reported, pigs from first litters were smaller than those from later litters but the author felt that a worm infestation might have caused these results.

Sinclair and Syrotuck (1928) found that age had no effect on gestation length and that on the average, older sows have larger litters. They also found a higher percentage of still born and immature pigs in litters from older sows. They found that pigs from older sows were larger at eight weeks than were pigs from younger sows.

Kuhlman and Cole (1929) reported very little difference between the average birth weight of pigs from yearling sows and those from older sows but at 56 days the 207 pigs from gilt dams averaged 23.02 pounds as compared with 27.10 pounds for the 227 pigs from older dams. They attributed this difference partly to the slightly higher birth weight of the pigs from the older dams and partly to the greater uniformity of the pigs in litters out of the older dams and to the better care these dams gave their pigs. Just what constituted this better care is not clear.

As a result of a study comparing crossbreeding and purebreeding for pork production, Musson (1934) concluded (1) the variation between years was significant, (2) the influence of the sow on her litter was conspicuous and highly significant, (3) the results of the Yorkshire crossing indicated that there may be wide differences between crossbreds of different combinations, (4) differences between birth and weaning data were too small to allow definite conclusions as to the superiority of one or the other, but crossbreds were slightly higher, (5) the feedlot data indicated conclusively that the crossbreds were superior to the purebreds in average daily gains and in feed consumed per hundred pounds of gain.

Dschaparidse (1935) found no seasonal influence on the size of the litters at farrowing or at the end of four weeks.

Bywaters (1936) found that (1) pigs weaned in the fall were, in general, heavier than those weaned in the spring (fall av. 44.34, spring av. 38.69 lbs.), (2) the mean square between ten seasons was highly significant, (3) a highly significant difference existed between the average weaning weights of pigs weaned by dams of the several ages making up a season, (4) the number of pigs weaned in a litter had little effect on the weaning weight of the individual pig therein. He was so impressed with the environmental influences that he said if "some means is devised for correcting the raw data for the age of dam and seasonal effects, many of the difficulties encountered in this study will be avoided".

Kronacher and Hundsdorfer (1936) studied the ten week weights of 822 pigs representing two breeds and an F_1 cross. They found no significant difference between males and females but the pigs weaned in the summer were a little larger than those weaned in the winter.

Vestal (1936) found at the Indiana Experiment Station that yearling sows averaged about two pigs less than sows 2, 3, 4, and 5 years old, but that the latter differed little from each other.

The review of "other published material on crossbreeding of swine" presented by Lush, Shearer, and Culbertson (1939) is excellent. This author was sure he could not equal their treatment of the material covered, so he presumed it permissible to copy a large portion of their review, as follows:

> Hammond (1922) studied the weights of hogs of several breeds and crosses at several ages up to about 11 months, as shown at the Smithfield Stock Show in England. He says, "In several cases the cross is larger than the heavier of the parent breeds . . . In many instances where the difference in weight between the breeds crossed is large, the

cross, although not actually heavier than the largest parent, is heavier than the mean of the parent breeds.

Callsen (1931) says that the results of four swine feeding experiments conducted in Germany give only an approximate idea of the usefulness of different breeds, but they have shown in general that the best feeding qualities for fattening were obtained from a healthy crossbred animal with a natural capacity for fattening received from the purebred parents. The crossbreds were not kept as breeding stock after the first generation.

In its annual report for 1927 the Illinois Agricultural Experiment Station describes the performance of some crossbred and purebred offspring produced by double mating a Duroc Jersey boar and a Poland China boar with Duroc Jersey and Poland China gilts. In a preliminary test on one double-mated litter, the two purebred pigs averaged 185 pounds at 6 months of age and the four crossbreds averaged 235 pounds at the same age. These pigs were not in a definitely planned experiment but both groups were raised under similar conditions. In the first year of the planned experiment there were two lots of 5 and 6 purebred pigs and two lots of crossbreds containing 7 and 14 pigs, respectively. The pigs in the purebred lots made daily gains of 1.53 and 1.57 pounds with feed requirements of 391 and 401 pounds per 100 pounds of gain. Those in the crossbred lots made daily gains of 1.77 and 1.64 pounds at feed requirements of 400 and 378 pounds. In a second year of work, the unpublished data, which were supplied to us by the Illinois station, show little difference in the average daily gain of 26 purebreds and 16 crossbreds, the actual figures being 1.49 pounds for the former and 1.50 pounds for the latter. The feed requirement for the purebreds was 426 pounds for 100 pounds of gain, compared to 418 pounds for the crossbreds. In a third year, 27 crossbreds averaged 1.79 pounds in daily gain compared to 1.71 pounds for 29 purebreds. The crossbreds in this year used 405 pounds of feed for 100 pounds of gain compared to 398 pounds for the purebreds. In verbal summaries and comments which have appeared in annual reports and in agricultural papers, the Illinois workers have stated that these experiments did not show a statistically significant difference in favor of the crossbreds. With characteristics showing as much individual variability as these do, it would require a large amount of data to establish with high statistical significance the reality of average differences as small as 10 percent or less. The lack of statistical significance may possibly have been due to the scantiness of evidence. The actual averages from the Illinois station show roughly the same amount of difference in average daily gain in favor of the crossbreds as was found by most workers, although the difference in feed requirements is smaller.

Shaw and MacEwan (1936), of the University of Saskatchewan, in reporting the weaning weights of 91 purebred pigs and 700 crossbreds produced by various combinations of five breeds, give the average weight of all purebreds as 35.7 pounds as compared with 39.4 pounds for all crossbreds. In the feeding trials 77 purebred pigs gained an average of 1.15 pounds per day and required 440 pounds of feed for each 100 pounds of gain as compared to 1.24 pounds daily gain and a feed requirement of 429 pounds for 325 crossbreds.

McMeekan (1936) in Australia compared purebred, crossbred and grade litters up to 56 days of age and says, "The purebreds compared very favorably with the first-cross litters and the grade litters by the purebred boars. The figures do not, therefore, support the contention often made that it is necessary to go to the first cross to obtain prolificacy, thriftiness, and rapid rate of growth." In his data, 202 litters of purebred pigs of four breeds had a death loss of 21.2 percent up to weaning time, as compared to 12.8 percent mortality for the 65 litters making up the various crossbreds. The average number of pigs in the crossbred litters was slightly smaller at birth but slightly larger at weaning time than in the purebred litters.

In a study of the records of the Smithfield Livestock Show in England for the years 1914 to 1933, inclusive, Whetham (1935) found that at a weight of 60 pounds the purebreds were slightly younger (93 days), but at heavier weights the crossbreds were younger. At 225 pounds the crossbreds averaged 10 days younger than the purebreds of the same weight. In another study of data taken from the same source, in which the average daily gains of all crossbreds are compared with those of all pigs of 12 pure breeds for the years 1924 to 1936, inclusive, it was found that for the 13 years the crossbreds averaged 1.28 pounds per day while the purebreds averaged 1.21 pounds. In only 2 of the 13 years did the average of the purebreds excel that of the crossbreds.

Several other European workers report experiments, all of which show varying degrees of advantage for crossbred pigs over purebreds.

The Minnesota Agricultural Experiment Station in 1928 began an experiment in which three types of crossbreds were produced: First-cross, three-breed cross and back-cross. All were found superior to the purebreds, with the three-breed cross having the greatest advantage. Crossbred sows were more efficient producers of pork than purebreds, producing litters which averaged from two-thirds to two more pigs per sow at weaning time and from 5 to 7 pounds more per pig at weaning time. The litters from the crossbred sows averaged from 63 to 96 pounds heavier at weaning time than the litters from the purebreds. The crossbred pigs reached a weight of 225 pounds from 17 to 22 days earlier than comparable purebreds and required from 27 to 36 fewer pounds of grain to do so.

The Missouri Agricultural Experiment Station reports a comparative feeding trial in 1936, in which 20 purebred Duroc Jersey pigs and 20 purebred Poland China pigs were compared with 20 pigs representing reciprocal crosses of the two breeds. The crossbred pigs made an average daily gain of 1.34 pounds per day and required 320 pounds of feed per 100 pounds of gain. The purebred Poland Chinas averaged 1.26 pounds in daily gain on a feed requirement of 300 pounds for each 100 pounds of gain. The purebred Duroc Jerseys gained 1.08 pounds per day and required 317 pounds of feed per 100 pounds of gain.

Kyzer and Clyburn, of the South Carolina Agricultural Experiment Station, report the results from a Poland China sow double-mated to a Poland China and a Duroc Jersey boar. The litter thus produced contained four crossbred pigs and three purebred Poland Chinas. Three crossbred and two purebred pigs were raised, fed separately after weaning, and carried to a final weight of 200 pounds. The crossbred pigs averaged 64 pounds at the beginning of the feeding period, made an average daily gain of 1.92 pounds and consumed 311 pounds of corn and 19 pounds of fishmeal per 100 pounds of gain. The purebred pigs averaged 56 pounds at the beginning of the feeding period, made an average daily gain of 1.86 pounds and consumed 333 pounds of corn and 21 pounds of fishmeal per 100 pounds of gain.

At the North Dakota Agricultural Experiment Station, Shepperd and Severson (1933) found no advantage, either in rate of gain while on feed or in desirability of carcass for Wiltshire sides, for crosses between lard and bacon breeds of hogs over the pure breeds. Their studies involved 386 purebreds of the bacon breeds, 635 purebreds of the lard breeds and 311 crosses between lard and bacon breeds. Their work was done over a period of 7 years beginning in 1925 and ending in 1931.

Robison (1938), at the Ohio Agricultural Experiment Station, compared 23 purebred litters of three breeds with 20 litters produced by various first crosses of the same breeds. He also compared 13 purebred litters of two breeds with 11 litters produced by mating crossbred sows with boars of a third breed. (See table 6, Lush, Shearer and Culbertson.)

The following data were furnished by the Bureau of Animal Industry, United States Department of Agriculture, from breeding experiments conducted over a period of 6 years (1927-32) at the United States Range Livestock Experiment Station, Miles City, Montana, in cooperation with the Montana Agricultural Experiment Station. Purebred animals of the Chester White and Yorkshire breeds were used.

Matings were planned each year to produce a group of purebred Yorkshire pigs, a group of purebred Chester White pigs and two groups of crossbred pigs, one from Chester White dams mated with Yorkshire boars and the other from Yorkshire dams mated with Chester White boars.

Although there was little difference in the size of litters farrowed or in the average birth weight of the pigs in the different groups, there was a considerable advantage, on the average, in the crossbred pigs at weaning, both in the number of pigs weaned per litter and in weaning weights. That the crossbred pigs were more vigorous at birth is shown by the lower death losses during the suckling period. Yorkshire dams producing purebred pigs weaned 78 percent of those pigs which were alive when farrowed, while those producing crossbred pigs weaned 84 percent. The Chester White dams producing purebred litters weaned 72 percent of those farrowed alive, while those producing crossbreds weaned 78 percent. The Yorkshire and Chester White sows farrowing crossbred pigs weaned 0.4 and 0.8 more pigs per litter than sows of the same breeds producing purebred pigs. At weaning the crossbred pigs were also heavier than the purebreds. There was also an increased economy in the production of weanling pigs in the crossbred groups, amounting to 9 percent for the pigs from Yorkshire sows and 14 percent for the pigs from Chester White sows.

From weaning to market weight, there was very little difference in the rate or economy of gains of the two crossbred groups. Each of these groups made somewhat more rapid gains and utilized their feed somewhat more efficiently than either group of purebreds.

Lush, Shearer and Culbertson (1939) studied records of 1,015 pigs farrowed in 108 litters, including Land. x PC crosses as well as those made with the Duroc Jersey, PC and York. breeds. Conclusions reached were as follows:

1. Crossbred pigs were somewhat more vigorous at birth than purebreds, as shown by their ability to survive until weaning age.

2. Crossbred pigs averaged about 3 or 4 pounds heavier at weaning time than purebreds. The weaning weight (total) of crossbred litters averaged more than for comparable purebred litters, partly because of the larger size of the pigs in the crossbred litters and partly because the crossbred litters on the average contained slightly more pigs at weaning time.

3. The crossbred sows observed in this study proved to be efficient pig producers, either when mated back to a boar of one of the parent breeds or to a boar of a third breed. When sired by a purebred boar the pigs from the crossbred sows, either backcross or three-breed cross, compared favorably with the first-cross pigs.

4. There is some general reason to suppose that breeds differ in their response to crossing and also that families or strains within breeds differ, but not enough evidence to determine which breeds can be expected to cross best with each other, nor whether distinct families which cross better than others exist and can be identified and maintained within pure breeds.

5. Crossbred sows may be used successfully for breeding if the boar is a purebred. In this way the hybrid vigor of the crossbred dam in nursing and rearing pigs may express itself enough to more than compensate for her lower value as a transmitter of inheritance.

6. Planless and unsystematic crossing may quickly result in a mongrel herd from which the owner will get neither profit nor pride of ownership.

7. In general it is the opinion of extension workers, farmers, and others in contact with this type of work that crossbred pigs gain a little more rapidly on slightly less feed than do purebreds. They also report larger litters of more vigorous pigs at farrowing and weaning time when crossbreeding is practiced.

A report from Kurmark (region around Berlin) (1940) on 11 years of swine production recording says that among more than 25,000 litters the "young sows" (about one-third of the total) farrowed 1.09 less pigs per litter than "old sows".

Tables 1 and 19 of Lush and Molln (1942) summarize for comparison the results of 15 investigations (11 European and 4 American) pertaining to regression of productivity on age of sow. Each study included at least 700 litters and presented averages at each age. All the studies showed almost exactly the same general picture. From the first to the second litter an increase of .68 pig occurred, from the second to the third litter an increase of another .68 pig, and then the increase slowed down.

The conclusion drawn by Lush and Molln (1942) from their results was that breed differences and station differences were both real and that there was not enough real interaction between them to be of much practical importance.

Robison (1944) reported that mating boars of one line to single cross females of two other lines has resulted in more pigs saved per litter at market age, fewer runts, faster gains, and greater gains per unit of feed than resulted from mating unrelated outbred boars and sows.

On the basis of results with breed crosses of noninbred stock, Winters et al. (1944) concluded that crosses involving three or perhaps four lines will produce pigs which are better than either crossbred or outbred pigs.

Dickerson, Lush, and Culbertson (1946) reported that crosses exceeded inbreds by 3.4 pounds at 56 days and by 25 pounds at 154 days. In total litter weight at 154 days, crosses exceeded inbreds by 290 pounds. "These facts suggest that using the best of such improved lines in topcrossing on outbred sows or in triple crosses offers opportunity for surpassing the performance of outbreds."

The most striking results of the analysis of the single cross data available to Henderson (1948) were "the apparent small differences among lines in general combining ability, the lack of any evidence of maternal differences among lines, and the relatively large differences among specific effects." Since his was the first study in which these sources were estimated, the results could not be compared directly with any previous results. The present study was an attempt to furnish estimates from an outbred population of swine of maternal effects which would be comparable to the maternal effects as defined by Henderson.

Maternal differences as defined by Henderson include both pre-natal and post-natal effects and are due entirely to differences among lines in genes influencing mothering ability. He explained that the reason why genetic differences among lines in their maternal abilities can be isolated in crosses among inbred lines is the fact "that each line is used both as the male parent and as the female parent, and consequently, the maternal effect can be estimated by comparing the performance of each line with respect to these two characteristics". Estimates from an outbred population of swine comparable to Henderson's were arrived at in this study by using two breeds, the Poland and the Landrace, both as male parent and as female parent and comparing the performance of the reciprocal crosses.

Squiers, et al. (1949) studied inbreeding and strain influences on components of fertility in sows. Ovulation rate for 214 gilts averaged 11.0, with a range from 10.4 to 12.0; the rate for 48 older sows averaged 15.7, ranging from 13.9 to 17.8. Total mortality to 25 days averaged 46 percent for gilts and 43 percent in older sows.

Chambers and Whatley (1950) found that three-linecross litters contained 1.7 more pigs and were 2.98 pounds heavier at 180 days than single cross litters. Heterosis was expressed to a greater extent in increased viability of the pigs and productivity of the crossline gilts than in the increased growth rate of the pig or its efficiency of gain.

In a study of causes of variation in 154-day weights of 2137 three-way cross pigs, Magee (1951) found the differences among the genic values of the lines, season-place groups, litters within three-way cross season-place subclasses, and pigs within litters to be important causes. The maternal effects of the lines and the interactions between the different effects were not statistically significant.

Warren and Dickerson (1952) presented several observations and conclusions pertinent to this study: (1) they found marked effects of seasons (confounded with age of sow), so they used the method of fitting constants to remove bias from season influences on crosses; (2) litter size at birth and weaning differed no more between lines of sire or dam than would be expected from the variation within crosses if no real line effect existed; (3) differences between lines of sire and of dam in weaning weight of pigs approached significance; (4) there were large and real line of sire and line of dam differences in 154-day weights of pigs; (5) line of dam accounted for nearly twice as much of the variation in 154-day weights and daily gain from weaning to market weight as did line of sire (23 vs. 12 and 30 vs. 17), "indicating that both transmitted and direct maternal influences were important". They drew their conclusions from reciprocal matings of two inbred Poland lines crossed with nine different stocks of five breeds.

After reviewing the results of swine breeding research over a long period of years at all the stations making up the Regional Swine Breeding Research Laboratory, Craft (1953) stated that "results indicate that lines should be selected for 'nicking', or combining ability, to get the most from linecrossing, within a breed and between breeds." He stated in a later paragraph that age of gilts at time of breeding showed important effects on the number of eggs shed and the number of pigs farrowed per litter.

Dickerson, et al. (1954) made a cooperative study of the amount and effectiveness of selection applied during the development of inbred lines of swine at several of the experiment stations participating in the Regional Swine Breeding Laboratory. Their data included 4,521 litters from 38 lines during the period 1932 to 1948. Litter size and weight were adjusted to a first litter basis. Conclusions with respect to the amount of selection applied and its effectiveness were not pertinent to this study.

As a result of a study of prenatal mortality in swine, Lasley (1955) concluded that maternal influence was present for number of corpora lutea and litter size.

Carmon, et al. (1956) derived equations for predicting the performance of rotations from the performance of the parent lines or breeds and their single crosses. On the basis of their equations, they conclude it is possible for a breeder to predict the best possible rotation for use with the specific lines, breeds or families available to him. Their assumptions are many, and they admit that the assumption of no epistasis is one that might seriously affect the results.

III. STATISTICAL METHODS EMPLOYED

A. Plan of Analysis

The first step in the study was to determine what corrections should be made to eliminate the effects of season, farm, and age of dam so that litters from sows that farrowed in different seasons, on different farms, and at different ages could be compared fairly. In the second step, the corrected data were used in a number of different analyses to determine the importance of differences between various breeding groups.

In the variance component analysis the data were examined to determine the importance of differences between breeding groups of sows, breeds of boars, and of interaction between breeding groups of sows and breeds of boars. "Interaction" is the amount by which differences between breeding groups of sows varied from breed to breed of boar or by which differences between breeds of boars varied from breeding group to breeding group of sow more than would be expected from the variation or sampling error within breeding groups of sows bred to the same breed of boar. By the size of this interaction it was possible to judge whether the differences between breeding groups of sows or breeds of boars in these data represented general differences between those breeding groups or breeds, or whether the observed differences were in large part peculiar to the special samples of each breeding group of sow bred to each breed of boar.

Section IIIB is an outline of the method used for both steps enumerated in paragraph one above. The general case of the method that was followed in adjusting for "fixed" effects may be found in Henderson (1952).

B. The Least Squares Analysis of Non-orthogonal Data

Brandt (1933) and Yates (1933, 1934) were the first to publish on the least squares method of analysis of multiple classifications with disproportionate subclass numbers. Brandt's method was restricted to a 2 x n classification. Yates extended the analysis to a p x q classification and presented the general theory of tests of hypotheses and the computation of sampling errors. Wilks (1938) and Hazel (1946) described the least squares analysis of a more than two-way classification and introduced an independent variable such as appears in the analysis of covariance. The method of analysis of non-orthogonal data was presented in detail by Henderson (1948) in order to introduce the notation and to describe the methods he developed for adjusting least squares estimates when the effects are assumed to be randomly drawn.

The theory of variance component analysis was treated by Crump (1947, 1951) and by Eisenhart (1947). These papers and most of the published works on estimating variance components deal with the one-way classification, with "nested" classifications, and with factorial classifications having equal subclass numbers. In these cases, estimation of variance components is usually accomplished by computing the mean squares in the standard analysis of variance, equating these mean squares to their expectations and solving for the unknown variances. These techniques are described in many statistical textbooks.

Unfortunately, research workers in some of those fields in which much use is made of variance component estimates are unable to obtain data which have the above described characteristics. This is particularly true of the present study where the subclasses are of quite unequal size due to differences in litter numbers.

Henderson (1952) described three methods for estimating variance components in the non-orthogonal case. The three methods described are:

1. Compute sums of squares as in the standard analysis of variance of corresponding orthogonal data. Equate these sums of squares to their expectations obtained under the assumption that all elements of the linear model save μ are regarded as random variables and solve for the unknown variances.

2. Obtain least squares estimates of fixed effects, "correct" the data according to these estimates of the fixed effects and then, using the corrected data in place of the original data, proceed as in Method 1.

3. Compute mean squares by a conventional least squares

analysis of non-orthogonal data (method of fitting constants, weighted squares of means, e.g.). Equate these mean squares to their expectations and solve for the unknown variances.

These three methods vary greatly in computational labor. Method 1 is the simplest. Method 2 in many cases is only slightly more difficult. Method 3 is usually much the most laborious. Henderson explained, however, that Method 1 leads to biased estimates if certain elements of the model are fixed or if some of them are correlated. He said that estimates obtained by Method 2 are free of the first of these biases, but not of the second, and that Method 3 yields unbiased estimates, but the computations required may be prohibitive. Method 2 was used in the present study.

The least squares method is usually the method of choice in a study such as this one because of several desirable properties (Henderson), namely;

(1) The estimates are unbiased, that is, $E(\hat{\theta}) = \theta$, where θ is the parameter being estimated and $\hat{\theta}$ is the least squares estimate of θ.

(2) The sampling error for each estimate is as small or smaller than any other estimate which can be obtained by taking linear combinations of the sample values.

(3) The computations can always be carried out.

(4) The method provides a straightforward way for obtaining the variance-covariance matrix of the parameter estimates.

(5) Parameter estimates can be made independently of any assumption with regard to the distribution of e_{ijk}.

(6) If the e_{ijk} are assumed to be normally distributed, tests of hypotheses can be affected using the F distribution, and confidence intervals can be computed. Furthermore, the least squares estimates are identical to the maximum likelihood estimates, and the tests of significance are identical to the likelihood ratio tests.

(7) The method provides a means for obtaining the maximum amount of information from a set of data with disproportionate subclass frequencies.

Practically speaking, the least squares method provides a computational procedure not only for correcting data for extraneous sources of variation preparatory to estimating a set of population values, but it also provides a method for obtaining sums of squares freed of the extraneous sources of variation. Estimates of population variances can then be obtained from these "corrected" sums of squares.

Comparison of these computational procedures with those described for balanced designs illustrate very vividly the great saving in labor which can be effected if the designs are completely balanced. Also, troublesome questions such as what assumptions to make regarding the presence or absence of interaction have no bearing on the balanced design. Furthermore, the information obtainable on each of the crosses considered in this study would be of equal precision in a balanced design.

IV. RESULTS AND DISCUSSION

A. The Source and Scope of the Data

The animals used in this study were the progeny of boars of eighteen inbred Poland China lines, seven Landrace, one Montana No. 1 line, and the Duroc, Chester White, Yorkshire, and Hampshire breeds crossed with ten different stocks of females ranging from purebreds to combinations of four breeds. All animals were maintained at two farms of the Iowa Agricultural Experiment Station in cooperation with the Regional Swine Breeding Laboratory. Eighty-two crosses are represented in this study, and these, with the number of litters represented in each, are enumerated in Table 25. A legend of the breeding of the boars is as follows:

Poland China Lines

A	Alliance
B	Blackbird
C	Charmer
D	Defender
E	Enterprise
G	Grandee
S	Scoutmaster
1Q	Line formed from A x G
5Q	Univ. of Ark. line
6Q	Gracious Lady
Ax	Line formed from A

Br	Brown Poland China
U	Univ. of Ark. Poland China
A_M	Minn. Line A Poland China
C_M	Minn. Line C Poland China
Mo	Missouri Line 6 Poland China
8Q	
11Q	Brown Poland China
Landrace	
L_I	Iowa Landrace
L_B	Beltsville Landrace
L_N	L_I X L_B
1B	Beltsville Line 1B
2B	Beltsville Line 2B
3B	Beltsville Line 3B
4B	Beltsville Line 4B
Other Breeds	
H	Montana No. 1 (Hamprace)
Du	Duroc
W	Chester White
Y	Yorkshire
Hamp	Hampshire

It was decided for purposes of this study that the maximum amount of information could be obtained for a given amount of computation by considering the litter as the experimental unit. The computations involved in a study of this nature are extremely laborious at best, so it seemed desirable to work with different measurements on the same experimental unit in order that the coefficients in the least squares equations, the elements of the inverse matrices, and the expected values of the different reductions in sums of squares would be the same for each measurement. The computations required to analyze thoroughly the data with respect to all of the five different measurements on litters were less than those that would have been required to analyze only one criterion for litters and one for individual pigs. Therefore, in measuring litter size at birth, 56 and 154 days, the total number of pigs in the litter was considered the experimental unit; in measuring weights at 56 and 154 days the average weight per pig in the litter was chosen as the experimental unit.

There is difference of opinion shown in the literature as to whether average weight per pig or total weight of the litter should be used as the experimental unit for weight. The total litter weight is a function of both litter size and average weight per pig. This author wished to study size and weight as separate characteristics, so he chose to use average weights. This, of course, is not free of criticism, because of the fact that the standard deviation of the average weight per pig in the litter varies as a function of number of pigs in the litter. The more pigs in a litter, the smaller will be the standard deviation of their average weight, and vice versa. Therefore, the error variance of average weights would include errors of measurement due to unequal litter sizes.

As shown in Table 25, the two major classifications of the data were breeding of boar and breeding of sow. The number of breeding types of boars considered was thirty and the number of breeding types of sows was ten.

Data for the present study were taken beginning with litters born in the fall of 1950 and ending with litters born in the spring of 1954. Those data available prior to the fall of 1950 have been previously analyzed and those since the spring of 1954 have become available since this study began. As many cross-line and crossbred litters as possible were produced, the number depending upon the physical facilities and the availability of females above the requirements for maintaining the purebred and pure line stocks.

Although it was not possible to produce all of the desired crosses in any one breeding season, it was planned to eventually produce litters that would fulfil all the purposes enumerated. The general plan was to start with lines developed at the Iowa Agricultural Experiment Station for producing first cross females and to breed these females to boars of other breeds, many of which were from lines developed at other experiment stations. After weaning the pigs were grouped according to age and fed in large lots containing a little pasture. The particular cross had no bearing on the group in which the individual pig was fed. Feeding and management practices were as nearly alike from one breeding season to the next as it was possible to make them. The following data were obtained for all of the litters:

1. Number of pigs, dead or alive, at birth.

2. Weight of the individual pig at birth (each pig was ear-notched at the time of weighing).

3. Weights of individual pigs at 56 days and 154 days. If the weighing was not done exactly at these ages, corrections were applied according to the formulas developed by Whatley (1937). One weight only was taken at 56 days, but in the case of 154 day weights one weight was obtained a short time prior and a second weight a short time subsequent to 154 days, and the two adjusted weights were averaged to obtain the 154 day weight for each pig.

Table 25 vividly illustrates the difficulty in obtaining a balanced design for testing when it is necessary at the same time to maintain lines and breeds and furnish pigs to fulfil other commitments. The number of litters obtained for different crosses varied from zero to 163 and it was possible to test only 82 of the 300 possible crosses during the four years. The large number of missing subclasses and the unequal numbers in the subclasses illustrate why a least squares solution was needed to obtain estimates of components of variance.

B. The Mathematical Model

In order to obtain answers to the questions proposed in Section I a mathematical model was developed which appeared to be a reasonable description of the underlying biology and which was at the same time amenable to statistical treatment. The following linear hypothesis was therefore assumed.

$$y_{ghijkl} = \mu + s_g + f_h + a_i + b_j + s_k + (bs)_{jk} + e_{ghijkl},$$

where

$$g = 1, \ldots\ldots, 8 \qquad h = 1, 2. \qquad i = 1, 2. \qquad j = 1, \ldots\ldots, 30 \qquad k = 1, \ldots\ldots, 10 \qquad l = 1, \ldots\ldots, n_{ghijk}$$

$$\sum_g \sum_h \sum_i \sum_j \sum_k n_{ghijk} = N$$

y_{ghijkl} denotes the value of the l^{th} experimental unit of the progeny resulting from a mating between a boar of the j^{th} breed and a sow of the k^{th} breeding type, born of a sow that was in the i^{th} age group on the h^{th} farm in the g^{th} season; $(bs)_{jk}$ is peculiar to all records made by litters produced from crossing the j^{th} breed of boar and the k^{th} breeding type of sow. μ is an effect common to all litters.

In most sets of data there are certain extraneous factors of which account should be taken. Some of these in the case of the swine data used for this study were season in which litters were born, age of dam, and farm on which the litters were born. The simplest way to take into account such differences is to adjust the data by means of suitable correction factors. Since, however, few such correction factors are available for swine, it is often necessary to obtain correction factors from the data at hand. Additive correction factors were computed and applied by adding s_g, f_h, and a_i to the linear mathematical model. s_g is an effect common to all litters born in the g^{th} season, f_h is an effect common to all litters born on the h^{th} farm, and a_i is an effect common to all litters born to dams of the i^{th} age. The s_g, f_h, and a_i were assumed to be constants.

e_{ghijk} is a random element peculiar to the $ghijkl^{th}$ litter. It is assumed to be normally and independently distributed with mean = zero and variance = σe^2. This error variance includes errors of Mendelian sampling, failure of the mathematical model to fit perfectly the actual biology of the material, and a multitude of environmental factors which cannot be measured.

C. Adjustments for Environmental Effects

1. Adjustment of ROP - pasture differences in 154-day weights

Pigs from 423 of the 1360 litters used in this study were jointly used in Record of Performance testing. This means four pigs from each of the 423 litters were placed in separate pens with overhead shelter and a concrete floor, and were full fed a balanced fattening ration. All the other litters, 937 in number, were raised in pasture lots. This treatment difference affected only 154-day weights, because the pigs were not placed on ROP test until they were 56 days of age.

The differences in 154-day weights between ROP and pasture raised pigs were due to two main effects, only one of which was removed. In the first place, the heaviest pigs in a litter were usually placed on ROP test, causing the difference in 56-day weights to account for a portion of the difference in 154-day weights. This portion was estimated on the basis of a value of two pounds for the regression of 154-day weight on 56-day weight. It was left in the data, because it was not due to treatment (ROP vs. pasture). The remainder of the difference between ROP and pasture raised pigs was considered to be due to treatment, and was substracted from the average weight per pig at 154 days on the basis of the ratio of the number of pigs placed on ROP test to the total number of pigs in the litter.

A numerical example will help make the explanation clear. The figures represent all pigs in litters from which ROP pigs were chosen.

First farrowing season (fall, 1950), 46 litters

	56-day weights	154-day weights
ROP	7410/178 = 42 lbs.	39560/178 = 222 lbs.
Pasture	4152/108 = 38 lbs.	18863/108 = 175 lbs.
Difference	4 lbs.	47 lbs. total
	b = 2 lbs.	-8 lbs. due to
Differences in 56-day weights		
		39 lbs. due to
Treatment		

If four pigs from a litter of five were found to have been on ROP test, 4/5 of 39 pounds (31 pounds) was substracted from the average 154-day weight of that litter. If four pigs from a litter of eleven were placed on ROP test, 4/11 of 39 pounds (14 pounds) was subtracted from the average 154-day weight of that litter. All litters that supplied pigs for ROP test were adjusted similarly.

2. Least squares adjustments and sampling errors of adjustments for differences due to seasons, farms and ages of sows

As mentioned in describing the mathematical model, it was necessary to decide what sources of variation in addition to differences due to breeding should be taken into account in the analysis. Some of the extraneous factors thought important enough to consider in the analysis were age of sow, farm on which the litter was raised, and season in which the litter was farrowed. The possibility of using correction factors was soon abandoned since there appeared to be none available which one could be sure was applicable to the particular data at hand.

General environmental changes, alike for contemporary sows from one season to the next, may include different kinds of things such as variations in the average weather conditions, in the kinds of pasture, in the average incidence of infection or parasitism, in the general feeding or management plan, etc. The effects of one of these various ingredients of seasonal changes could not be separated from the effects of the others in these data, but their combined or joint effect was measured.

A preliminary analysis of 154 day weights showed that the differences among the eight seasons were too large to be disregarded in the analysis. The test of hypothesis that seasons = zero resulted in the following analysis of variance:

	d.f.	Mean Square
Among seasons	7	3958.86
Error	1352	563.21

Then an inspection of the marginal means with respect to seasons for each of the five litter measurements made it plain that the tests of significance of season differences for the other four criteria of classification in addition to 154 day weight would result in mean squares for seasons which would be significantly larger than mean squares for error. The fact that seasonal differences were of consequence in this set of data was unfortunate from the standpoint of appraising the crosses, since the distribution of crosses tested from year to year was quite unbalanced. Consequently, the sampling errors of the estimates are higher than they would be if it were not necessary to consider seasonal differences. However, it should be pointed out that differences among the eight seasons were only slightly confounded with annual changes in the genetic merit of the crosses since there was considerable carryover of sows and boars from one year to the next.

Farm differences may have been caused mostly by environmental differences in management, feeding, housing, care, etc., but may in part have resulted from differences in the average genetic composition of herds kept at the two farms. It was hoped, of course, that farm differences were caused by environmental differences.

Preliminary analysis of 154 day weights showed that the differences among the two farms were so large they had to be accounted for in the analysis. The test of hypothesis that farm differences were zero was accomplished from the following analysis of variance:

	d.f.	Mean Square
Among farms	1	100091
Error	1358	507

Inspection of the marginal means with respect to farms for each of the five litter measurements made it evident that the tests of significance of farm differences for the other four criteria of classification in addition to 154 day weight would result in mean squares for farms which would be significantly larger than mean squares for error. As with the 154 day weights, there was some confounding of differences among the two farms with genetic merit of the crosses because eight of the 84 crosses were produced on only one farm, involving 148 of the 1360 litters studied. Three of these crosses were produced at Napier and the other five were produced at Ankeny.

It is well known from previously reported work that age of sow accounts for a significant amount of variation among litters. An inspection of the marginal means made it obvious that the present study was no exception. Since the majority of litters included in this study were first litters and few sows were kept for more than two litters, and since it was desirable to keep the age classes to a minimum, the groupings chosen were first litter and second or later litter.

The extraneous factors encountered in the present study may be understood more clearly by referring to the accompanying graph showing the means for each season of birth of the litters, and the tables of means for the two farms and the two ages of sows.

The graph of season means shows that there is a general increase with time for all five characters, as well as fluctuations up and down from one season to the next. In making adjustments for these differences, season 5 (Fall, 1952) was arbitrarily chosen as the base. This means that

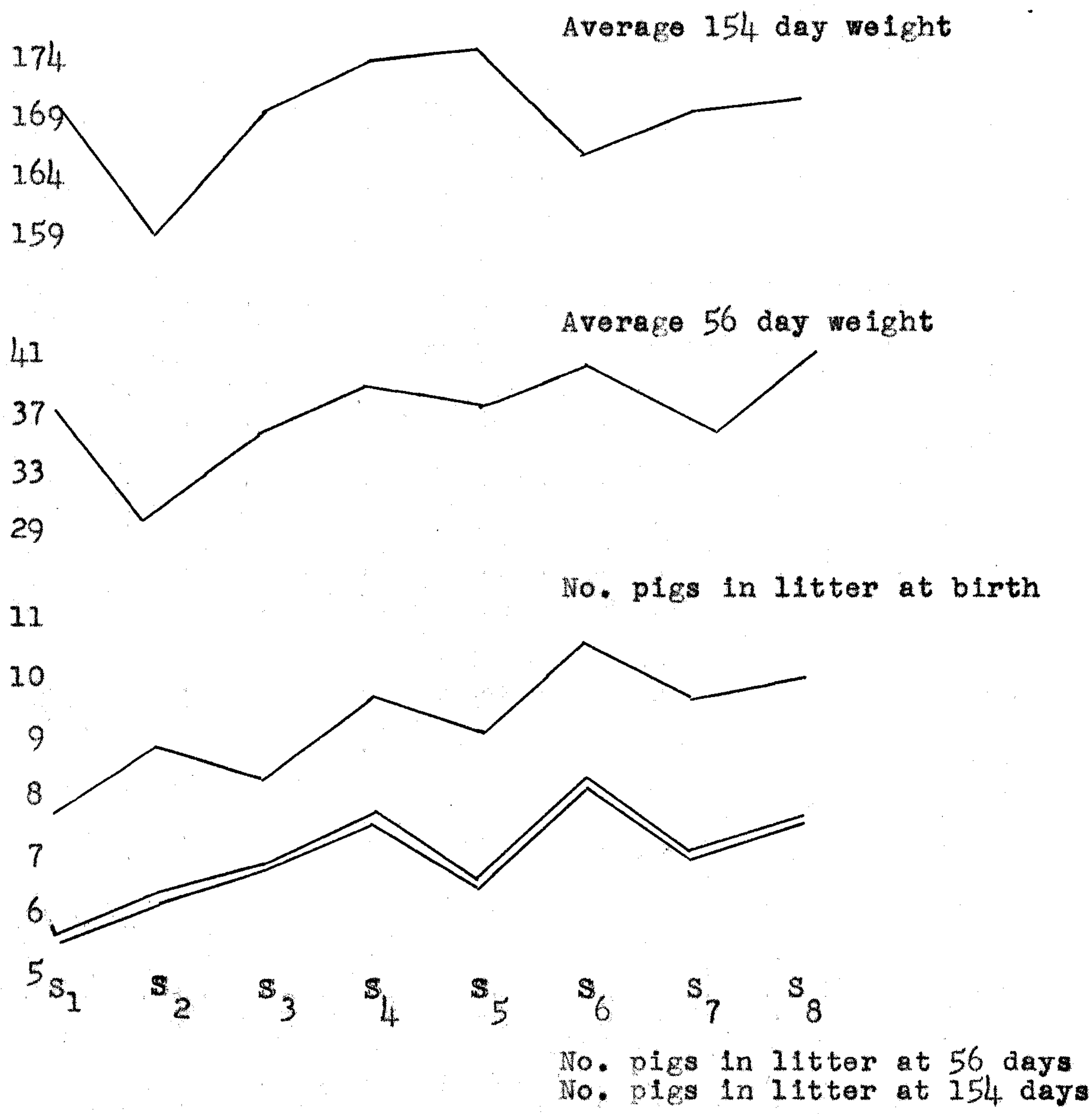

Figure 1. Graph showing seasonal means of each of the five characteristics under consideration.

the adjustment for season of birth applied to litters born in the Fall of 1952 was zero, and amounts were added to litters born in the other seasons according to whether the seasonal means were below or above that of the Fall of 1952. Comparison of the unadjusted differences with the constants computed after fitting s_g, f_h, and a_i (Table 5) furnished a check as to the reliability of the corrections. In general, the agreement was very close.

Table 1. Means of the five characteristics by farm and by age of sow.

	Ankeny	Napier	Gilts	Sows
Litter size at birth	9.9	8.7	8.7	10.0
Litter size at 56 days	7.4	6.3	6.7	7.4
56-day weight	35.4	37.2	34.6	39.2
Litter size at 154 days	7.3	6.2	6.6	7.2
154-day weight	163.0	176.4	165.2	173.3

Comparison of the means of the two farms showed that the Napier litters were smaller than the Ankeny litters at all three ages, but that the loss in pig numbers was almost the same for both farms from birth to 56 days, and from 56 days to 154 days. The Napier pigs weighed more, on the average, than Ankeny pigs. The author feels this was due to better management on the Napier farm than the Ankeny farm, and not to the fact that the Napier litters were smaller than the

Ankeny litters. More space and labor are available at Napier, and the pigs can be given better treatment and handling than those at Ankeny.

The corrections computed to adjust for the difference between farms were quite close to the differences in the means. The Napier litters were adjusted, so the three corrections for litter size were positive, and the two for average weight per pig in the litter were negative.

Comparison of the means of gilt litters and sow litters showed that in all five characteristics the sows' productivity was superior to that of the gilts. The litters born of sows were the ones corrected; all five adjustments computed using the least squares method were near the magnitude of the unadjusted mean differences.

In computing the adjustments each litter was classified in three different ways according to age of dam, farm, and season:

	Symbol	No. constants
Age of dam	a_i	two, $i = 1, 2$
Farm	f_h	two, $h = 1, 2$
Season born	s_g	eight , $g = 1, \ldots, 8$

The objective was to fit the twelve constants for a, f, and s plus μ, and then to adjust all the data, using International Business Machines, before proceeding with analyses of variance.

The data from which the equations were formed came from a study of 1360 litters of pigs where the following categories were considered:

Season of birth

Farm

Age of dam

Breeding of boar

Breeding of sow

Meas. on 5 characters

The subclass numbers were unequal, and showed considerable range. Since a litter was born in one season only, on one farm only, and of a sow that was only one age, these were considered the discontinuous variables whereas the breeding categories listed above were the continuous variables. A study such as this may be extended to cover as many continuous variables as desired.

The problem was to find estimates of the coefficients (lower case letters) so that the litter size or weight could be adjusted for any litter born under the conditions here listed.

Using the data as indicated for the particular category involved, the thirteen equations were set up (Table 2). The μ equation was based on the total number of litters in each category, said total numbers becoming the coefficients of the lower case letters for which the values were found. The total number of litters was 1360. The sum of the μ number of litters for the S's, for the F's, and for the A's must each

Table 2. Coefficients of original or least squares equations.

	μ	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8	f_1	f_2	a_1	a_2		Litter Size at Birth
(1) μ	1360	115	150	139	181	227	228	187	133	813	547	699	661	=	12808
(2) s_1	115	115								44	71	44	71	=	885
(3) s_2	150		150							83	67	85	65	=	1325
(4) s_3	139			139						71	68	75	64	=	1153
(5) s_4	181				181					96	85	76	105	=	1749
(6) s_5	227					227				147	80	156	71	=	2128
(7) s_6	228						228			117	111	118	110	=	2425
(8) s_7	187							187		138	49	129	58	=	1814
(9) s_8	133								133	117	16	16	117	=	1329
(10) f_1	813	44	83	71	96	147	117	138	117	813		435	378	=	8030
(11) f_2	547	71	67	68	85	80	111	49	16		547	264	283	=	4778
(12) a_1	699	44	85	75	76	156	118	129	16	435	264	699		=	6164
(13) a_2	661	71	65	64	105	71	110	58	117	378	283		661	=	6644

Table 3. C_{ij} matrix.

	$\hat{s}_1$	$\hat{s}_2$	$\hat{s}_3$	$\hat{s}_4$	$\hat{s}_6$	$\hat{s}_7$	$\hat{s}_8$	$\hat{\mu}$	$\hat{f}_1$	$\hat{a}_1$
$\hat{s}_1$	115							115	44	44
$\hat{s}_2$		150						15~~1~~0	83	85
$\hat{s}_3$			139					139	71	75
$\hat{s}_4$				181				181	96	76
$\hat{s}_6$					228			228	117	118
$\hat{s}_7$						187		187	138	129
$\hat{s}_8$							133	133	117	16
$\hat{\mu}$	115	150	139	181	228	187	133	1360	813	699
$\hat{f}_1$	44	83	71	96	117	138	117	813	813	435
$\hat{a}_1$	44	85	75	76	118	129	16	700	435	699

therefore equal 1360. Substituting the μ values in the general equation: $1360\hat{\mu} + 115\hat{s}_1 + 150\hat{s}_2 + 139\hat{s}_3 + 181\hat{s}_4 + 227\hat{s}_5 + 228\hat{s}_6 + 187\hat{s}_7 + 133\hat{s}_8 + 813\hat{f}_1 + 547\hat{f}_2 + 699\hat{a}_1 + 661\hat{a}_2 = 12808$ (for litter size at birth).

The coefficient matrix (Table 3) was established by imposing the restrictions that $\hat{s}_5 = \hat{f}_2 = \hat{a}_2 = 0$, and rearranging the equations for ease of computation.

By inverting the matrix of coefficients of Table 3, the C^{ij} pertaining to the constants were obtained. These are presented in Table 4. The necessity for carrying six decimals may be seen by looking at the $C^{6\cancel{9}10}$ value. This is such a small

Table 4. C^{ij} matrix.

$\hat{s}_1$	$\hat{s}_2$	$\hat{s}_3$	$\hat{s}_4$	$\hat{s}_6$	$\hat{s}_7$	$\hat{s}_8$	$\hat{\mu}$	$\hat{f}_1$	$\hat{a}_1$
.013582	.004581	.004634	.004733	.004654	.004311	.004741	-.005555	.000795	.000953
	.011085	.004483	.004525	.004491	.004359	.004543	-.004841	.000285	.000395
		.011704	.004557	.004519	.004347	.004553	-.004968	.000408	.000463
			.010179	.004575	.004356	.004803	-.005184	.000314	.000865
				.008916	.004349	.004598	-.005010	.000395	.000536
					.009762	.004469	-.004200	-.000308	.000018
						.013223	-.005135	-.000913	.001942
							.007124	-.001970	-.002132
								.003309	-.000238
									.003319

number that four or five decimals would be inadequate to furnish two significant digits. Estimates of the constants were then computed by summing the products of the C^{ij} and the right hand sides for each row of the C^{ij} matrix and column of right hand sides. These are presented in Table 5.

Chapter 6 of Kempthorne (1952) may be consulted as a clear and complete explanation of the general case of the analysis of multiple classifications and the problems of the estimation of components of variance.

Kempthorne (1952) suggests that a convenient method of solving equations similar to these is to augment them by introducing another unknown. Then the coefficient matrix can be inverted. However, the computations will be shortened by imposing restrictions similar to those imposed above, thus reducing the number of equations to the number of independent parameters (degrees of freedom).

Imposing the restrictions $\Sigma \hat{s}_g = \Sigma \hat{f}_h = \Sigma \hat{a}_i = 0$ and augmenting the equations by introducing another unknown should, of course, lead to solutions which are equivalent to those resulting from imposing the restrictions $\hat{s}_5 = \hat{f}_2 = \hat{a}_2 = 0$. This author solved the equations shown in Table 2 by imposing both sets of restrictions, in order to gain a better understanding of the methods of matrix inversion, and in order to check his calculations. After the constants estimated by imposing the restrictions $\Sigma \hat{s}_g = \Sigma \hat{f}_h = \Sigma \hat{a}_i = 0$ were adjusted to the base season, farm, and age of

Table 5. Estimates of constants imposing restrictions $\hat{s}_5 = \hat{f}_2 = \hat{a}_2 = 0$.

Estimate	Litter Size at Birth		Litter Size at 56 Days		56-Day Weight		Litter Size at 154 Days		154-Day Weight	
	Unadj.	L.S. Est.	Unadj.	L.S. Est.	Unadj.	L.S. Est.	Unadj.	L.S. Est.	Unadj.	L.S. Est.
$\hat{s}_1$	-1.6	-1.8 ± 0.4	-0.7	-0.7 ± 0.3	0.2	-1.9 ± 0.9	-0.7	-0.7 ± 0.3	-3.2	-9.8 ± 2.8
$\hat{s}_2$	-0.5	-0.6 ± 0.3	0.1	-0.0 ± 0.3	-7.3	-8.1 ± 0.8	-0.2	-0.2 ± 0.3	-15.0	-17.4 ± 2.5
$\hat{s}_3$	-1.0	-1.1 ± 0.3	0.4	0.4 ± 0.3	-1.3	-2.4 ± 0.8	0.4	0.4 ± 0.3	- 4.3	-7.7 ± 2.6
$\hat{s}_4$	0.4	0.1 ± 0.3	1.3	1.2 ± 0.3	1.5	0.0 ± 0.7	1.1	1.1 ± 0.3	- 0.6	-4.5 ± 2.4
$\hat{s}_5$	0	0	0	0	0	0	0	0	0	0
$\hat{s}_6$	1.3	1.2 ± 0.3	1.8	1.8 ± 0.3	2.8	1.6 ± 0.7	1.8	1.7 ± 0.3	- 8.8	-12.3 ± 2.3
$\hat{s}_7$	0.4	0.3 ± 0.3	0.8	0.7 ± 0.3	-2.2	-1.8 ± 0.7	0.8	0.7 ± 0.3	- 6.3	-4.8 ± 2.4
$\hat{s}_8$	0.7	-0.4 ± 0.3	1.2	0.5 ± 0.3	4.0	2.8 ± 0.8	1.2	0.6 ± 0.3	- 5.0	-5.8 ± 2.8
$\hat{f}_1$	1.2	1.2 ± 0.2	1.1	0.9 ± 0.2	-1.8	-4.0 ± 0.4	1.1	0.9 ± 0.2	-13.4	-16.1 ± 1.4
$\hat{f}_2$	0	0	0	0	0	0	0	0	0	0
$\hat{a}_1$	-1.3	-1.4 ± 0.2	-0.7	-0.8 ± 0.2	-4.6	-3.7 ± 0.4	-0.6	-0.7 ± 0.2	- 8.1	-7.8 ± 1.4
$\hat{a}_2$	0	0	0	0	0	0	0	0	0	0
$\hat{\mu}$	9.4	9.6 ± 0.3	7.1	6.3 ± 0.2	36.9	42.1 ± 0.6	6.9	6.2 ± 0.2	169.1	190.1 ± 2.0

Table 6. Adjustments computed from table 5.

Estimate	Litter Size at Birth	Litter Size at 56 Days	56-Day Weight	Litter Size at 154 Days	154-Day Weight
$\hat{s}_1$	1.8	0.7	1.9	0.7	9.8
$\hat{s}_2$	0.6	0.0	8.1	0.2	17.4
$\hat{s}_3$	1.1	-0.4	2.4	-0.4	7.7
$\hat{s}_4$	-0.1	-1.2	0.0	-1.1	4.5
$\hat{s}_5$	0	0	0	0	0
$\hat{s}_6$	-1.2	-1.8	-1.6	-1.7	12.3
$\hat{s}_7$	-0.3	-0.7	1.8	-0.7	4.8
$\hat{s}_8$	0.4	-0.5	-2.8	-0.6	5.8
$\hat{f}_1$	0	0	0	0	0
$\hat{f}_2$	1.2	0.9	-4.0	0.9	-16.1
$\hat{a}_1$	0	0	0	0	0
$\hat{a}_2$	-1.4	-0.8	-3.7	-0.7	- 7.8

dam they were found to be equivalent to those resulting from the restrictions $\hat{s}_5 = \hat{f}_2 = \hat{a}_2 = 0$.

It was then a simple matter to convert the constants into the adjustments shown in Table 6.

Some consideration should be given to the question of whether or not restricting these correction factors to an additive scheme introduced so much error as to raise serious doubt about the validity of later conclusions. To begin with, the mathematics of any other scheme would be prohibitive of using it, so an additive scheme had to be employed.

Examination of the graphs in Figure 1 showed the seasonal changes to be generally linear over all seasons. There were only two farms involved, so differences due to farms were linear.

The two classifications used for age of dam should be adequate, since 699 litters were gilt litters, while 661 were second litters. Actually 112 of these were third or later litters, but were combined with the second litters in order to keep the number of age of sow classes to a minimum. This did introduce some error, which made the estimated difference between first and second litters too large (Lush and Molln, 1942), but these sows made up only one-fifth of those considered as second litter sows, and the error thus introduced should not be extreme enough to invalidate any conclusions drawn from the corrected data.

The data were then corrected for the s', f's, and a's. This was done by correcting each litter rather than correcting subclass and class totals. International Business Machines were used, and the corrected data were punched into the same cards that contained the original data.

D. Analyses and Tests of Hypotheses

1. Comparison of Poland China inbred lines where boars were crossed with Landrace sows

There were 83 litters of pigs involved in this phase of the study. Nine lines of boars were compared on the basis of the five characteristics mentioned previously. Means for the characteristics within each sire line are shown in Table 7.

Table 7. Means of Poland China sire lines.

Line of Boar	Number Litters	L. Size at Birth	L. Size 56 Days	56 Day Weight	L. Size 154 Days	154 Day Weight
A	26	9.0	6.5	35.9	6.4	179.3
B	6	11.6	8.9	36.8	9.1	170.9
C	6	10.8	7.1	33.8	7.2	150.4
D	3	11.8	8.2	34.9	7.8	162.5
E	1	4.9	3.8	36.7	3.8	153.8
G	37	10.5	7.1	35.9	6.9	180.0
S	2	9.2	7.0	42.2	7.0	194.3
U	1	6.6	4.4	32.2	4.3	137.7
1Q	1	9.2	5.0	31.0	4.9	148.0
Total	83	10.5	7.0	35.8	6.9	175.5

A conventional least squares analysis was completed. Differences between the lines for litter size at birth and 154 day weight were significant at the five per cent level. Mean squares for litter size at 56 and 154 days and average weight per pig at 56 days were found to be no larger than would be expected due to sampling. The mean squares, estimated mean differences due to lines computed using the least squares method, their standard errors, as well as the order of rank of the lines, are shown in Table 8. The lines ranked as shown in Table 8 both in the table of means and the magnitude of the constants fitted. All the estimates save four were smaller than their standard errors, the large size of the standard errors being a consequence of the small number of litters involved in this phase of the study and the extreme disproportionality between the lines (Table 7).

It was not safe to conclude from these statistics that a real difference existed between the inbred lines of Poland boars, but it seems that, given sufficient numbers, statistical significance could be demonstrated. There was an estimated range of 5.3 pigs in litter size at 154 days and an estimated range of 56.6 pounds in average 154 day weight, which would amount to a great deal of marketable product to the producer. Two of the highest ranking lines, A and G, are being used extensively in commercial swine production by private breeders.

Table 8. Mean squares and ranking of lines for each characteristic.

L. Size at Birth		L. Size 56 Days		56 Day Weight		L. Size 154 Days		154 Day Weight	
D	2.6 ± 3.3	B	3.9 ± 2.9	S	11.2 ± 8.5	B	4.2 ± 2.9	S	46.3 ± 22.8
B	2.4 ± 3.1	D	3.2 ± 3.1	B	5.8 ± 7.5	D	2.9 ± 3.1	G	32.0 ± 18.9
C	1.6 ± 3.1	G	2.1 ± 2.8	E	5.7 ± 9.8	C	2.3 ± 2.9	A	31.3 ± 19.0
G	1.3 ± 2.9	C	2.1 ± 2.9	G	4.9 ± 7.0	S	2.1 ± 3.3	B	22.9 ± 20.2
S	0.0 ± 3.5	S	2.0 ± 3.3	A	4.9 ± 7.0	G	2.0 ± 2.8	D	11.5 ± 21.5
1Q	0.0	A	1.5 ± 2.8	D	3.9 ± 8.0	A	1.5 ± 2.8	E	5.8 ± 26.4
A	-0.2 ± 2.9	1Q	0.0	C	2.8 ± 7.5	1Q	0.0	C	2.4 ± 20.2
U	-2.6 ± 4.1	U	-0.6 ± 3.8	U	1.2 ± 9.8	U	-0.6 ± 3.9	1Q	0.0
E	-4.3 ± 4.1	E	-1.2 ± 3.8	1Q	0.0	E	-1.1 ± 3.9	U	-10.3 ± 26.4

Mean squares, lines and error

d.f.	L. Size at Birth	L. Size 56 Days	56 Day Weight	L. Size 154 Days	154 Day Weight
9	19.06*	6.69	17.82	7.16	933.15*
74	8.29	7.35	47.59	7.40	348.13

2. Comparisons of purebreds and reciprocal crosses between Landrace and Poland China

A total of 595 litters was used in determining whether there was a difference between Poland-Landrace and Landrace-Poland litters in the five characteristics measured. The data were arranged as shown in the table of means (Table 9) so that comparisons could also be made between pure breeds and crossed breeds.

Table 9. Means of litters used in Poland-Landrace vs. Landrace-Poland comparisons.

	L. Size at Birth		L. Size 56 Days		56-Day Weight		L. Size 154 Days		154-Day Weight	
♀	P	L	P	L	P	L	P	L	P	L
♂										
P	8.5	10.5	5.6	7.0	32.0	35.8	5.6	6.9	155.7	175.5
L	7.5	9.4	5.1	5.7	34.1	33.0	5.1	5.5	168.0	148.1

First the data were analyzed according to the rough classifications between cells and within cells. Then Duncan's (1955) Multiple Range Test was applied to the sums of squares between cells in order to make the individual comparisons desired. It was found that each cross differed significantly from the other three in size of litters at birth and in 154-day weight. Litter size at 56 days appeared to be similar for Landrace-Poland, Purebred Poland, and Purebred Landrace litters, but all three of these were significantly lower than the Poland-Landrace litters. Weight at 56-days showed the least variation of any of the five characteristics. The two pure breeds differed significantly from the cross-bred litters of the two breeds, but the Landrace-Poland and Poland-Landrace crossbred litters did not differ significantly, the mean difference between the two being only 1.7 pounds. Litter size at 154 days differed little among purebred Poland, purebred Landrace and Landrace-Poland litters, but all three were significantly lower than the Poland-Landrace litters. It is apparent from the foregoing analysis that the Poland-Landrace litters are significantly better than the Landrace-Poland litters in all characteristics except 56-day weight. The advantage is in favor of the Poland-Landrace cross in 56 day weight also, even though it is not significant.

It is noteworthy that in all three of the litter size characteristics the Landrace-Poland litters were actually inferior to either of the two pure breeds.

3. Comparison of Duroc and Chester White boars crossed on Poland-Landrace sows; Poland-Landrace versus Landrace-Poland sows, a test for maternal effects

The development of systematic rotational crosses requires the consecutive crossing of several breeds of boars upon the crossbred females from the last boars used in the cycle. This problem is difficult to investigate experimentally because of the large number of combinations of crosses possible among the several breeds of swine and because of the possibility of differences in maternal effects. In the present experiment, two breeds, the Duroc and the Chester White, were chosen because of their availability and because of the particular characteristics of those breeds. A total of 466 litters were involved in this comparison; the distribution of litters according to the breeding of the boars and of the sows is shown in Table 10.

Table 10. Number of litters involved in comparing Duroc and Chester White boars and test for maternal effects.

	Breeding of Sows		
Boars	P x L	L x P	Total
Duroc	179	148	327
Chester White	97	42	139
Total	276	190	466

In the preceding section, crosses of Poland boars on Landrace females were superior in litter size and growth rate to market age to the crosses of Landrace boars on Poland sows. The question was investigated in this section concerning whether the crossbred females differed in productivity depending upon whether they were made by crossing Landrace boars on Poland sows or by crossing Poland boars on Landrace sows. If the superiority of the Landrace females in producing first crosses is caused by autosomal genes and there is no carryover of maternal effects, the crossbred females from reciprocal crosses should be approximately equal in productivity.

Analyses of variance were completed for all five characters using the method for a 2 x 2 table with disproportionate subclass numbers as outlined by Snedecor (1946). Estimates of mean differences due to boars and sows were computed by both the method of fitting constants and using the weighted means. Variance components were computed using Henderson's Method 1. These results are shown in Tables 12, 13 and 14.

One of the most interesting facts in this analysis is the high mortality in litters sired by Chester Whites. The half pig difference in favor of Chester White boars when the litters were born was significant at the 5% level. The 1/4 pig difference in favor of Duroc boars when the litters reached 56 and 154 days was not statistically significant. However, the biological significance of these results is clear. Chester White boars have the ability to sire larger litters than Duroc boars, but their pigs are subject to higher mortality at early ages.

Duroc boars also showed a distinct ability to sire litters of higher average weight per pig. This advantage amounted to approximately seven pounds per pig at 154 days of age. Clearly, litters sired by Duroc boars will furnish more mar-

Table 11. Means compared in present section of study.

	L. Size at Birth		L. Size 56 Days		56-Day Weight		L. Size 154 Days		154-Day Weight	
Boars / Sows	PxL	LxP	PxL	LxP	PxL	LxP	PxL	LxP	PxL	LxP
Duroc	9.7	9.8	7.2	7.1	36.8	35.4	7.1	7.1	177.7	170.0
Chester White	10.3	10.2	6.7	7.2	34.6	33.9	6.6	7.1	164.7	169.8

Table 12. Completed analyses of variance.

		Mean Squares				
Source	d.f.	L. Size at Birth	L. Size 56 Days	56-Day Weight	L. Size 154 Days	154-Day Weight
Boars	1	30.5*	4.0	292.2**	6.6	5933.6**
Sows	1	0.0	0.0	72.7	0.0	952.3
Interaction	1	0.2	1.9	3.5	2.7	1031.6
Error	462	6.5	5.6	37.8	5.7	358.1

Table 13. Estimates of mean differences.

Unadjusted

Duroc-Ch.White	-.56	.31	1.80	.37	7.93
PxL - LxP	.03	-.14	.93	-.13	3.19

Fitting Constants

Duroc-Ch.White	-.53	.29	.22	.26	1.86	.66	.25	.27	6.56	.72
PxL - LxP	.00	.29	-.23	.26	1.01	.66	-.23	.27	1.32	.72

Weighted Means

Duroc-Ch.White	-.57	.30	1.98	.36	8.58
PxL - LxP	.05	-.39	.80	-.42	2.29

Table 14. Estimates of components of variance.

	L. Size at Birth	L. Size 56 Days	56-Day Weight	L. Size 154 Days	154-Day Weight
σ_b^2	0.23	0.02	1.09	0.024	5.37
σ_s^2	-0.005	-0.004	-0.016	-0.021	- 21.2
σ_{bs}^2	-0.05	-0.01	0.42	0.007	37.10
σ_e^2	7.06	5.66	37.82	6.19	446.4

ketable product than litters sired by Chester White boars, when crossed on Poland-Landrace sows.

Results of comparing Poland-Landrace and Landrace-Poland sows showed no significant differences to exist, thus indicating that there was no maternal effect due to the way in which the two breeds were originally crossed. These results are in agreement with those of Henderson (1948).

Estimates of variance components were computed as a matter of interest to see how they compared with estimates computed using all 1360 litters involved in this study. There was a great deal of difference in the two sets of estimates, especially for the components due to sows. Evidently the sampling errors in these data are large, and render the estimates of components of variance almost useless.

4. Comparison of Beltsville strains, Yorkshire and Hampshire breeds

Part of the experimentation involved in this study was devoted to comparing boars of the Beltsville strains and the Yorkshire and Hampshire breeds when crossed on Duroc-Poland-Landrace sows. There were 136 litters produced over four breeding seasons at both farms to be used in this comparison. Two boars of each of the Beltsville strains were used. One Yorkshire and one Hampshire boar were used.

Means of the five characters measured were as shown in Table 15 for the strains and breeds compared. Least squares

Table 15. Means of Beltsville strains, Yorkshire and Hampshire breeds.

	L. Size at Birth	L. Size 56 Days	56 Day Weight	L. Size 154 Days	154 Day Weight	Number Litters
1B	10.3	7.4	35.5	7.3	172.9	40
2B	8.8	5.8	37.9	5.7	165.7	19
3B	9.6	6.4	35.1	6.2	168.6	29
4B	10.0	7.3	35.7	7.2	170.8	22
York.	11.2	7.6	35.5	7.7	171.7	10
Hamp.	10.3	7.5	39.0	7.6	194.7	16
Total	10.0	7.0	36.2	6.9	173.1	136

analyses of the differences between these means yielded only one significant F value, that one being 154-day weight. Examination of the mean 154-day weights made it apparent that the highly significant difference was due in most part to the superiority of Hampshire crosses over all others.

Rankings of the four strains and two breeds, along with mean squares and least squares estimates of the mean differences are shown in Table 16. Even though statistically significant differences did not exist between the strains and breeds for four of the characters, it is worthy of note that the Hampshire and Yorkshire breeds rank above the Beltsville strains in the final amount of marketable product.

This apparent superiority of the Hampshire and Yorkshire breeds in crosses with Duroc-Poland-Landrace sows may reflect

Table 16. Rankings and estimated mean differences.

L. Size at Birth		L. Size 56 Days		56 Day Weight		L. Size 154 Days		154 Day Weight	
Y	1.6 ± 1.0	Y	1.2 ± 0.9	Hamp	3.9 ± 2.2	Y	1.5 ± 1.0	Hamp	26.1 ± 5.9
1B	0.7 ± 0.7	Hamp	1.1 ± 0.8	2B	2.8 ± 2.1	Hamp	1.3 ± 0.9	1B	4.3 ± 4.6
Hamp	0.7 ± 0.9	1B	1.0 ± 0.7	4B	0.6 ± 2.0	1B	1.1 ± 0.7	Y	3.1 ± 6.9
4B	0.4 ± 0.8	4B	0.9 ± 0.8	Y	0.4 ± 2.6	4B	1.0 ± 0.8	4B	2.2 ± 5.3
3B	0.0	3B	0.0	1B	0.4 ± 1.8	3B	0.0	3B	0.0
2B	-0.8 ± 0.8	2B	-0.6 ± 0.8	3B	0.0	2B	-0.5 ± 0.8	2B	-2.9 ± 5.6
				Mean Squares, Breeds and Error					
d.f.									
6		8.28		8.52		40.72		10.55	1534.58**
129		7.87		7.14		51.82		7.54	353.37

the heterosis obtained from a fourth unrelated breed, since the Beltsville strains carry a high percentage of Landrace genes.

5. Backcrossing Duroc-Poland-Landrace sows to Poland or Landrace boars versus further crossing to a fourth breed

As experimentation in crossbreeding swine advanced it became important to determine at what stage in a rotational crossbreeding program the original breeds could be used again. Are there definite advantages in heterosis from using four or five breeds in a rotational cross as compared with only three? An answer to this question was attempted by crossing DPL females to Poland and Landrace boars as well as to several other breeds. Two hundred forty-six litter records were available to furnish a basis for these comparisons. They were farrowed over five breeding seasons at both farms. The Beltsville strains were pooled with the Landrace for this section of the study.

Means of the five characters are shown in Table 17 according to the breed of sire. Least squares analyses of these differences yielded a highly significant F value due to breed of boar for 154-day weight. The other F values were not significant, but the one for 56-day weight did approach significance at the 5% level. The large F value for 154-day weight is due largely to the fact that average 154-day weights of litters sired by Hampshire boars were about 17 pounds

Table 17. Means of six breeds of boars crossed on Duroc-Poland-Landrace sows.

	L. Size at Birth	L. Size 56 Days	56-Day Weight	L. Size 154 Days	154-Day Weight	Number Litters
P	10.1	7.5	34.0	7.4	164.9	29
L	9.8	6.8	35.9	6.7	169.7	117
C.W.	9.5	5.7	30.6	5.8	164.5	10
Y	11.2	7.6	35.5	7.7	171.7	10
Hamp.	10.3	7.5	39.0	7.6	194.7	16
H Mont #1	10.5	7.5	34.7	7.4	165.9	64
Total	10.1	7.1	35.4	7.1	169.7	246

heavier than the average weights of litters sired by boars of the other breeds. Actually, the boar has little effect upon the weight of his offspring until after the pigs are weaned (Lush and Molln, 1942), so there is little reason for expecting larger differences in any of the data except 154-day weights.

Rankings of the six breeds of boars crossed on Duroc-Poland-Landrace sows, as well as mean squares and least squares estimates of the mean differences are shown in Table 18. In general, the use of a fourth breed shows some advantage in litter size and weight since the litters by Hampshire, Yorkshire, and Montana No. 1 boars usually rank ahead of those by Landrace or Poland boars. The Chester White boars ranked last on every count, indicating that backcrossing

Table 18. Rankings and estimated mean differences.

L. Size at Birth		L. Size 56 Days		56-Day Weight		L. Size 154 Days		154-Day Weight	
Y	0.8 ± .9	Y	0.1 ± .9	Hamp.	4.3 ± 1.9	Y	0.3 ± 0.9	Hamp.	28.7 ± 5.2
H	0.0	P	0.1 ± .6	L	1.3 ± 1.0	Hamp.	0.1 ± 0.7	Y	5.8 ± 6.3
Hamp.	-0.2 ± .8	H	0.0	Y	0.8 ± 2.3	H	0.0	L	3.8 ± 2.9
P	-0.4 ± .6	Hamp.	0.0 ± .7	H	0.0	P	0.0 ± 0.6	H	0.0
L	-0.7 ± .9	L	-0.6 ± .4	P	-0.7 ± 1.5	L	-0.7 ± 0.4	P	-1.1 ± 4.2
C.W.	-1.0 ± .9	C.W.	-1.7 ± .9	C.W.	-4.1 ± 2.3	C.W.	-1.7 ± 0.9	C.W.	-1.4 ± 6.3

Mean Squares, Breeds and Error

d.f.					
6	6.20	7.30	92.03	8.30	1979.33**
239	7.40	6.59	44.63	6.77	347.85

to Landrace or Poland boars would be preferable to using the Chester White as a fourth breed to cross on Duroc-Poland-Landrace sows. The high mortality of crossbred pigs sired by Chester White boars on Poland-Landrace sows is also evident in these pigs from Duroc-Poland-Landrace sows.

The limited data here suggest that a four-breed rotation is preferable to one of three breeds only if a fourth breed of satisfactory production is available. If the choice of breeds is limited, the three-breed rotation is preferable to using a fourth breed which has poor crossing performance.

6. Performance of purebred and crossbred sows

Both crossbreeding and the crossing of inbred lines of swine have demonstrated that hybrid vigor is important for viability, rate and efficiency of growth, prolificacy and milking ability in swine. The average advantage of first-generation crossbreds over the parental purebreds amounts to about five per cent in litter size raised and four per cent in growth rate (Dickerson, 1952). Carcass composition and efficiency of feed utilization are improved less than rate of growth (Gregory and Dickerson, 1952) by crossbreeding. Prolificacy and milk production are improved markedly by crossbreeding (Winters, et al., 1935 and Lush, et al., 1939), partly due to the increased numbers of eggs produced by crossbred sows (Squiers, et al., 1952). Results from crossing inbred lines of swine provide additional evidence for the

Table 19. Number of litters involved in comparison of purebred and crossbred sows.

Boars	Sows	Poland s_1	Landrace s_2	P x L s_3	DPL s_4	HDPL s_5	Total
Poland	b_1	293	83		29	28	433
Landrace	b_2	162	57		117		336
Mont. 1	b_3			1	64		65
Duroc	b_4			327			327
Ch. White	b_5			139	10	21	170
York.	b_6				10	3	13
Hamp.	b_7				16		16
Total		455	140	467	246	52	1360

importance of heterosis in the economic characters of swine (Dickerson, et al., 1946; Hazel, et al., 1948; Robison, 1948; Sierk, 1948). Such results have led to proposals for deliberately selecting to produce lines that would give maximum heterosis when used in crosses for commercial pork production (Dickerson, 1951, 1952).

In the meantime, such differences as exist between breeds in general and specific combining ability can be utilized in commercial production. In addition, this information is useful in making plans for the development of lines which should cross well in commercial swine production.

Seven breeds of boars and five breeds or crosses of sows

Table 20. Means by breed of boar and breed or cross of sow.

	L. Size at Birth	L. Size 56 Days	56 Day Weight	L. Size 154 Days	154 Day Weight
Boar					
Poland	9.0	6.2	33.1	6.1	161.2
Landrace	8.6	5.9	34.6	5.8	165.3
Mont. 1	10.4	7.4	34.8	7.4	166.3
Duroc	9.7	7.1	36.2	7.1	174.2
Ch. White	10.3	6.7	33.9	6.6	164.9
Yorkshire	11.1	7.6	35.4	7.5	171.3
Hampshire	10.3	7.5	39.0	7.6	194.7
Sow					
Poland	8.1	5.5	32.8	5.4	160.3
Landrace	9.8	6.5	34.7	6.3	164.5
P x L	9.9	7.0	35.7	7.0	171.8
DPL	10.1	7.1	35.4	7.1	169.3
HDPL	10.7	7.3	34.0	7.1	166.4

were involved in this phase of the study (Table 19). Means are shown in Table 20. Constants were fitted to estimate mean differences due to breeds of boars and breeding types of sows, as shown in Tables 21A and 21B. Analyses of variance were completed for comparing the breeds of boars on one hand and the breeding types of sows on the other (Table 22). A highly statistically significant difference was found to exist

Table 21A. Mean differences between sows.

	Litter Size at Birth		Litter Size 56 Days		56-Day Weight		Litter Size 154 Days		154-Day Weight	
	Unadj.	Adj.	Unadj.	Adj.	Unadj.	Adj.	Unadj.	Adj.	Unadj.	Adj.
Poland	-0.7	-0.2±0.6	-1.5	-2.6±0.5	-2.9	-5.4±1.6	-1.6	-2.5±0.6	-11.5	-17.5±4.4
Landrace	-3.4	-0.3±0.6	-0.5	-1.6±0.6	-1.0	-3.6±1.7	-0.7	-1.5±0.6	- 7.3	-13.6±4.6
P x L	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
DPL	0.2	0.0±0.6	0.1	-0.8±0.5	-0.3	-3.2±1.6	0.1	-0.7±0.5	- 2.5	-10.4±4.4
HDPL	0.8	0.3±0.5	0.3	-0.4±0.5	-1.7	-2.5±1.4	0.1	-0.5±0.5	- 5.4	- 6.4±3.9

Table 21B. Mean differences between boars .

	Litter Size at Birth		Litter Size 56 Days		56-Day Weight		Litter Size 154 Days		154-Day Weight	
	Unadj.	Adj.	Unadj.	Adj.	Unadj.	Adj.	Unadj.	Adj.	Unadj.	Adj.
Poland	-0.7	0.7±0.6	-0.9	1.2±0.6	-3.1	1.6±1.6	-1.0	1.1±0.6	-13.0	2.6±4.5
Landrace	-1.1	-0.1±0.6	-1.2	0.6±0.6	-1.6	2.8±1.7	-1.3	0.4±0.6	- 8.9	5.5±4.6
H	0.7	0.7±0.7	0.3	1.1±0.6	-1.4	1.7±1.8	0.3	1.0±0.6	- 7.9	2.4±5.0
Duroc	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
C.W.	0.6	0.5±0.3	-0.6	-0.3±0.2	-2.3	-1.8±2.7	-0.5	-0.4±0.2	- 9.3	-7.8±1.9
York	1.4	1.3±0.9	0.5	1.2±0.8	-0.8	2.2±2.5	0.4	1.1±0.8	- 2.9	6.6±6.8
Hamp.	0.6	0.6±0.9	0.4	3.1±0.8	2.8	12.8±2.4	0.5	3.1±0.8	20.5	63.4±6.6

Table 22. Mean squares computed in analysis of variance of breeding types of sows and breeds of boars.

Due to	d.f.	L. Size at Birth	L. Size 56 Days	56-Day Weight	L. Size 154 Days	154-Day Weight
Types of sows	4	393.3	196.2	1311.5	185.1	27657.6
Breeds of boars	6	104.1	76.9	887.8	78.4	20448.7
Error	1349	6.3	5.6	49.5	5.7	369.1

between the breeds of boars and the breeding types of sows for all five characteristics measured.

The original choice of Duroc and Chester White boars for crossing on Poland-Landrace sows was determined largely by the availability of lines developed in the Regional Swine Breeding Laboratory. Relatively few lines of Yorkshire and Hampshire have been developed. As shown in section IV D 3, crossbred litters out of Duroc boars were definitely superior to those by Chester White boars. There is evidence in the present analysis that the Yorkshire and Hampshire breeds might have provided as good or better boars for crossing on Poland-Landrace sows than did the Duroc. While the test-matings were not made in such a way that exact comparisons can be made, the average performance of the Yorkshire and Hampshire boars is good enough so that this question should certainly be investigated further.

Durham, <u>et al.</u> (1952) compared gilts that were sired by inbred boars with gilts sired by non-inbred boars, and concluded that high productivity of gilts is more generally expressed as a heterotic effect than is rate of gain. Such is the case in the present study (Table 21A). These same authors mentioned that the usual tendency for larger number of pigs per litter to be associated with lighter individual pig weights was not found in their data, because the progeny of gilts sired by inbred boars excelled those of gilts sired by non-inbred boars both in number of pigs weaned and in individual pig weights. The same thing is apparent in the present study, but this general principle may account for the fact that the advantage in per cent for larger number of pigs is greater than the advantage in per cent for heavier individual pig weights.

E. Estimation of Components of Variance

Table 24 shows the number of litters in each of the subclasses according to breed of sire and dam. The DPL breeding of dam means a Duroc-Poland-Landrace crossbred, and the HDPL means a Hampshire-Duroc-Poland-Landrace crossbred.

Tables 25 through 29 show the corrected subclass and class means for the five characters under consideration.

The following sums of squares were computed for each character:

Table 23. Sums of squares of corrected data.

	Litter Size at Birth	Litter Size at 56 Days	56-Day Weight	Litter Size at 154 Days	154-Day Weight
T	217943.2	131105.4	1691763.2	129543.3	38376597.8
B	208410.3	123076.2	1621520.6	121450.9	37813846.8
S	208459.6	123067.7	1619659.2	121411.4	37758706.3
BS	208659.1	123286.4	1625510.4	121647.0	37871797.4
CF	207373.8	122284.4	1617608.6	120617.5	37722942.2

$$T = \sum_i \sum_j \sum_k y^2_{ijk} \qquad BS = \sum_i \sum_j \frac{y^2_{ij}}{n_{ij}}$$

$$B = \sum_i \frac{y^2_{i..}}{n_{i..}} \qquad CF = \frac{y^2_{...}}{N}$$

$$S = \sum_j \frac{y^2_{.j.}}{n_{.j.}}$$

These are presented in Table 23.

If the data were orthogonal, the sums of squares in the analysis of variance would be

Among breeding of boars	=	B - CF
Among breeding of sows	=	S - CF
Breeding of sire x breeding of dam	=	BS-B-S+CF
Error	=	T-BS

If these same quantities were computed in spite of the non-orthogonality and equated to their expectations, unbiased

Table 24. Number of litters in each of the subclasses and classes.

Sows	Inbred Poland	X-Line Poland	Iowa Land	Belt. Land	$L_I x L_B$	PxL_N	PxL	LxP	DPL	HDPL	Total
Boars											
A	12	38	22	2	2				5	5	86
B	5	21	6								32
C	1	5	6								12
D	4		3								7
E	4		1								5
G	33	55	31	4	2				11	15	151
S	5		2								7
Ax	3	2							2		7
Br		14									14
U		7		1							8
A_M	4	10							1		15
C_M	2	6							2		10
Mo	3	46							3	3	55
1Q		8		1						1	10
5Q									1	2	3
6Q		1									1
8Q									2	2	4
11Q	2	2							2		6
L_I	50	42		2	10				7		111
L_B	35	31	22		8						96
L_N	3		15								18
1B		1							40		41
2B									19		19
3B									29		29
4B									22		22
H							1		64		65
Du						16	163	148			327
W						12	85	42	10	21	170
Y									10	3	13
Hamp									16		16
Total	166	289	108	10	22	28	249	190	246	52	1360

Table 25. Corrected subclass and class means for litter size at birth.

Sows	Inbred Poland	X-Line Poland	Iowa Land	Belt. Land	$L_I x L_B$	PxL_N	PxL	LxP	DPL	HDPL	Total
Boars											
A	7.1	9.4	8.9	10.2	9.7				9.9	10.2	9.0
B	8.4	9.6	11.6								9.8
C	9.6	10.4	10.8								10.6
D	9.1		11.8								10.3
E	10.1		4.9								9.1
G	7.9	9.1	10.1	12.6	12.8				11.5	10.5	9.5
S	7.4		9.2								7.9
Ax	7.7	10.5							9.0		8.9
Br		8.3									8.3
U		7.3		6.6							7.2
A_M	5.2	8.4							8.0		7.5
C_M	9.0	7.2							12.0		8.5
Mo	5.0	8.5							7.3	11.1	8.4
1Q		5.5		9.2						14.0	6.7
5Q									10.5	11.0	10.8
6Q		8.1									8.1
8Q									9.0	8.5	8.8
11Q	8.0	7.5							8.0		7.8
L_I	6.9	8.1		12.7	7.4				9.3		7.7
L_B	7.6	7.4	9.4		11.3						8.3
L_N	9.2		9.3								9.3
1B		7.7							10.3		10.2
2B									8.8		8.8
3B									9.6		9.6
4B									10.0		10.0
H							8.5		10.5		10.4
Du						10.3	9.6	9.8			9.7
W						10.4	10.3	10.2	9.4	10.8	10.3
Y									11.2	10.8	11.1
Hamp									10.3		10.3
Total	7.5	8.5	9.7	11.2	9.5	10.4	9.8	9.9	10.1	10.7	9.3

Table 26. Corrected subclass and class means for litter size at 56 days.

Sows	Inbred Poland	X-Line Poland	Iowa Land	Belt. Land	$L_I x L_B$	PxL_N	PxL	LxP	DPL	HDPL	Total
Boars											
A	5.2	6.0	6.4	7.1	7.5				7.7	7.5	6.2
B	6.1	5.8	8.9								6.4
C	5.9	6.9	7.1								6.9
D	6.6		8.2								7.3
E	6.6		3.8								6.1
G	5.5	6.3	6.7	9.2	8.1				8.3	8.1	6.6
S	5.1		7.0								5.6
Ax	2.7	2.5							5.5		3.4
Br		5.3									5.3
U		5.1		4.4							5.0
A_M	2.2	5.4							8.0		4.7
C_M	6.5	4.6							7.5		5.6
Mo	3.0	5.9							5.9	9.1	5.9
1Q		3.6		5.0						9.6	4.3
5Q									8.5	6.0	6.8
6Q		5.2									5.2
8Q									8.0	7.0	7.5
11Q	4.0	5.5							6.0		5.2
L_I	4.5	6.1		7.7	4.2				6.9		5.3
L_B	5.0	5.3	6.2		5.8						5.5
L_N	3.8		5.7								5.4
1B		4.3							7.4		7.3
2B									5.8		5.8
3B									6.4		6.4
4B									7.3		7.3
H							6.4		7.5		7.4
Du						7.0	7.2	7.1			7.1
W						7.4	6.6	7.2	5.7	6.4	6.7
Y									7.6	7.8	7.6
Hamp									7.4		7.4
Total	4.9	5.8	6.6	7.6	5.5	7.2	7.0	7.1	7.1	7.3	6.5

Table 27. Corrected subclass and class means for 56-day weight.

Sows	Inbred Poland	X-Line Poland	Iowa Land	Belt Land	$L_I x L_B$	PxL_N	PxL	LxP	DPL	HDPL	Total
Boars											
A	33.6	32.7	35.9	38.7	33.0				37.6	29.9	33.9
B	32.7	31.0	36.8								32.4
C	35.3	31.6	33.8								33.0
D	35.6		34.9								35.3
E	31.3		36.7								32.4
G	30.6	33.1	36.2	31.6	39.4				31.9	37.9	33.6
S	30.5		42.2								33.8
Ax	22.0	24.5							28.5		24.6
Br		31.4									31.4
U		31.6		32.2							31.7
A_M	33.8	28.8							32.0		30.3
C_M	34.5	32.1							31.0		32.3
Mo	34.5	32.3							41.5	33.0	33.0
1Q		32.8		31.0						16.5	31.0
5Q									38.1	36.6	37.1
6Q		29.4									29.4
8Q									33.1	39.6	36.4
11Q	29.0	38.0							34.0		33.7
L_I	35.7	33.6		40.9	37.4				37.4		35.3
L_B	33.1	36.1	32.8		29.8						33.7
L_N	18.4		31.0								28.9
1B		22.8							35.5		35.2
2B									37.9		37.9
3B									35.1		35.1
4B									35.7		35.7
H							38.7		34.7		34.8
Du						38.4	36.7	35.4			36.2
W						35.4	34.5	33.9	30.6	32.2	33.9
Y									35.5	34.8	35.4
Hamp									39.0		39.0
Total	32.9	32.8	34.7	34.9	34.4	37.1	35.9	35.1	35.4	34.0	34.5

Table 28. Corrected subclass and class means for litter size at 154 days.

Sows	Inbred Poland	X-Line Poland	Iowa Land	Belt Land	$L_I x L_B$	$P x L_N$	PxL	LxP	DPL	HDPL	Total
Boars											
A	5.0	6.1	6.3	7.0	7.4				7.6	7.1	6.2
B	6.1	5.8	9.1								6.4
C	5.9	6.9	7.2								7.0
D	6.6		7.8								7.2
E	6.6		3.8								6.1
G	5.4	6.3	6.6	8.6	8.0				8.2	8.0	6.6
S	5.1		7.0								5.6
Ax	2.7	2.5							5.5		3.4
Br		5.4									5.4
U		4.9		4.3							4.8
A_M	2.2	5.3							7.0		4.6
C_M	6.5	4.7							7.5		5.6
Mo	3.0	5.9							5.9	9.1	5.9
1Q		3.4		4.9						8.7	4.1
5Q									8.5	6.0	6.8
6Q		5.1									5.1
8Q									8.0	7.0	7.5
11Q	4.0	5.0							6.0		5.0
L_I	4.5	6.1		8.0	4.1				6.7		5.3
L_B	5.0	5.1	6.1		5.4						5.3
L_N	3.7		5.3								5.1
1B		4.3							7.3		7.3
2B									5.7		5.7
3B									6.2		6.2
4B									7.2		7.2
H							6.5		7.4		7.4
Du						7.0	7.2	7.0			7.1
W						7.2	6.5	7.1	5.8	6.3	6.6
Y									7.7	6.8	7.5
Hamp									7.6		7.6
Total	4.9	5.7	6.5	7.3	5.2	7.1	6.9	7.1	7.1	7.1	6.4

Table 29. Corrected subclass and class means for 154-day weight.

Sows	Inbred Poland	X-Line Poland	Iowa Land	Belt Land	$L_I x L_B$	PxL_N	PxL	LxP	DPL	HDPL	Total
Boars											
A	161.0	154.1	179.9	174.6	177.5				168.4	160.5	163.9
B	152.4	147.3	170.8								152.5
C	135.0	151.8	150.4								149.7
D	161.0		162.5								161.7
E	145.8		153.8								184.2
G	154.3	160.9	179.7	178.5	188.1				170.6	180.8	166.8
S	152.4		194.2								164.4
Ax	115.0	137.0							128.0		125.0
Br		164.5									164.5
U		159.1		137.7							156.4
A_M	155.0	144.2							164.0		148.4
C_M	143.0	146.8							142.0		145.1
Mo	158.7	161.8							181.3	170.4	163.2
1Q		146.9		148.0						141.9	146.5
5Q									167.9	167.4	167.6
6Q		148.3									148.3
8Q									160.9	178.4	169.6
11Q	170.0	146.5							162.0		159.5
L_I	171.8	167.6		173.7	153.3				163.8		168.1
L_B	166.3	173.0	152.9		142.8						163.4
L_N	133.2		137.1								136.4
1B		134.7							172.9		172.0
2B									165.7		165.7
3B									165.2		165.2
4B									170.8		170.8
H							187.5		165.9		166.3
Du						182.7	177.1	170.0			174.2
W						161.6	165.2	169.8	164.5	156.4	164.9
Y									171.7	169.9	171.3
Hamp									194.7		194.7
Total	161.4	159.7	165.8	169.6	154.9	173.7	173.1	169.9	169.3	164.2	166.5

estimates of the variances would be obtained by solving the resulting equations. The necessary expectations were derived from Table 23. To illustrate, E (among breeding of boars) = E(B-CF) = E(B)-E(CF). The coefficients of μ^2 and the variances in these expectations were as shown in Table 30.

Table 30. Coefficients of μ^2 and the variances.

	μ^2	σ_b^2	σ_s^2	σ_{bs}^2	σ_e^2
T	N	N	N	N	N
BS	N	N	N	N	P
B	N	N	K_1	K_1	s
S	N	K_2	N	K_2	d
CF	N	K_3	K_4	K_5	1

N, s, d were defined in the statement of the linear model. The total number of filled subclasses = 82 = p.

$K_1, \ldots, K_5$ were computed as follows, using Table 24:

$$K_1 = \sum_i \frac{\sum_j n_{ij}^2}{n_{i.}} \qquad K_3 = \frac{\sum_i n_{i.}^2}{N}$$

$$K_2 = \sum_j \frac{\sum_i n_{ij}^2}{n_{.j}} \qquad K_4 = \frac{\sum_j n_{.j}^2}{N}$$

$$K_5 = \frac{\sum_{ij} n_{ij}^2}{N}$$

Table 31. Expectations of sums of squares shown in table 23.

	μ^2	σ_b^2	σ_s^2	σ_{bs}^2	σ_e^2
T	1360	1360	1360	1360	1360
BS	1360	1360	1360	1360	82
B	1360	1360	664	664	30
S	1360	419	1360	419	10
CF	1360	148	210	62	1

Next the amounts by which the coefficients of σ_e^2 were increased in the corrected as compared to the uncorrected sums of squares were needed. The subclass numbers in Table 32 were used for computing the P_{ij} pertaining to S. The P_{ij} values are shown in Table 33. The P_{ij} pertaining to BS, B, and CF were computed similarly.

Summing the products of corresponding entries in Tables 4 and 33, thus (.013582) (9.575) + ... + (.003319)(125.579) = 0.9959. Therefore, the coefficient of σ_e^2 in E (S) = 10 + 0.9959 = 10.9959. Similarly the addition to σ_e^2 in E (BS) = 0.8603, in E (B) = 0.4840, and in E (CF) = 0.3395.

Table 34 shows the corrected sums of squares and their

Table 32. Litter numbers for computing P_{ij} pertaining to S.

Breeding of sow	s_1	s_2	s_3	s_4	s_6	s_7	s_8	μ	f_1	a_1	Σ
0	38	26	30	9	17	21	0	166	32	72	411
1	59	64	17	46	20	17	42	289	211	119	884
2	6	12	13	16	31	5	11	108	29	56	287
3	0	2	0	0	4	0	1	10	2	8	27
4	0	0	2	4	1	2	11	22	15	4	61
5	12	16	0	0	0	0	0	28	0	16	72
6	0	25	29	30	52	29	21	249	168	136	739
7	0	4	48	65	24	12	0	190	142	106	591
8	0	0	0	11	61	75	39	246	190	148	770
9	0	0	0	0	18	26	8	52	24	34	162
	115	149	139	181	228	187	133	1360	813	699	4004

Table 33. P_{ij} pertaining to S.

s_1	s_2	s_3	s_4	s_6	s_7	s_8	μ	f_1	a_1
9.574	9.611	4.177	4.233	3.548	3.180	3.031	41.558	17.641	18.445
	11.504	5.054	6.109	6.196	3.882	4.345	53.331	25.604	25.362
		8.198	8.843	7.032	4.259	2.483	48.497	26.293	24.162
			12.256	16.648	5.316	4.921	60.662	39.397	30.454
				16.534	13.173	7.906	77.424	45.014	42.365
					14.408	7.262	62.588	38.501	34.428
						7.399	44.315	29.473	21.863
							506.124	269.692	238.194
								182.250	139.145
									125.579

Table 34. Corrected sums of squares and their expectations.

	μ^2	σ_b^2	σ_s^2	σ_{bs}^2	σ_e^2	L. Size at Birth	L. Size 56 Days	56-Day Weight	L. Size at 154 Days	154-Day Weight
BS	1360	1360	1360	1360	82.8603	208659	123286	1625510	121647	37871797
B	1360	1360	664	664	30.4840	208410	123076	1621521	121451	37813847
S	1360	419	1360	419	10.9959	208460	123068	1619659	121411	37758706
CF	1360	148	210	62	1.3395	207374	122284	1617609	120618	37722942

Table 35. Equations to be solved.

	σ_b^2	σ_s^2	σ_{bs}^2	σ_e^2	L. Size at Birth	L.Size at 56 Days	56-Day Weight	L.Size at 154 Days	154-Day Weight
B-CF	1212	454	602	29.1445	1037	792	3912	833	90905
S-CF	271	1150	357	9.6564	1086	783	2051	794	35764
BS-B-S+CF	-271	-454	339	42.7199	-873	-573	1939	-598	22187

expectations.

The equations to be solved are presented in Table 35. The first equation reads:

$$1212\ \sigma_b^2 + 454\ \sigma_s^2 + 602\ \sigma_{bs}^2 + 29.1445\ \sigma_e^2$$
$$= 1037 \text{ (for litter size at birth)}$$

The solutions to these equations are shown in Table 36. The estimates of σ_e^2 can be obtained readily from the residual sum of squares after fitting the constants, that is, from the total sum of squares minus the reduction due to fitting constants.

The values of the reductions are obtained by multiplying the constants times the right hand sides. For example, using Tables 2 and 5, the reduction due to fitting constants for litter size at birth is -(1.77) (885) - (0.62) (1325) ... - (1.43) (6164) + (9.57) (12808) = 122300. In general terms, the expected value of the reduction in sum of squares is obtained by inverting the matrix of coefficients in the least squares equations, multiplying each element of the inverse by the expected value of the products of the sums associated with the row and column of the element, and then summing all of such products.

Estimates of these components are useful in planning experiments and setting standards for magnitudes of sources of variation expected. Magnitudes computed in the present study are shown in Table 37, based on the assumption that the three negative components for interaction are zero.

Table 36. Solutions to equations of table 35.

	Litter Size at Birth	Litter Size at 56 Days	56-Day Weight	Litter Size at 143 Days	154-Day Weight
Total	133616	77946	1940577	75657	39804021
Reductions	122300	69023	1871968	66583	39059978
Residual sum of sq.	11316	8923	68609	9074	744043
Expectation	$1278\ \sigma_e^2$	$1278\ \sigma_e^2$	$1278\ \sigma_e^2$	$1278\ \sigma_e^2$	$1278\ \sigma_e^2$
$\hat{\sigma}_e^2$	8.85	6.98	53.68	7.10	582.19
$\hat{\sigma}_b^2$	0.94	0.69	1.20	0.73	42.17
$\hat{\sigma}_s^2$	1.08	0.77	0.76	0.78	5.84
$\hat{\sigma}_{bs}^2$	- 1.39	- 0.99	0.93	- 1.03	33.61

Table 37. Variance estimates of table 36 expressed as fractions of the totals of the estimates.

Fraction Estimated	L. Size at Birth	L. Size 56 Days	56-Day Weight	L. Size 154-Days	154-Day Weight
Total	10.87	8.44	56.57	8.61	663.81
σ^2_e / σ^2_T	.815	.828	.949	.825	.877
σ^2_b / σ^2_T	.086	.082	.021	.085	.064
σ^2_s / σ^2_T	.099	.110	.013	.090	.008
$\sigma^2_{bs} / \sigma^2_T$	0.	0.	.017	0.	.051

F. Correlations Among the Five Performance Traits

1. Correlations between size of litter at different ages

One would certainly expect a positive association between the three measures of litter size, because litter size at 56 and 154 days are influenced by litter size at birth. As shown in Table 38 there was a large and highly significant positive association between the three possible pairs of the three traits. The correlations are in close agreement with those reported by Warren and Dickerson (1952), Axelsson (1928), and other workers.

2. Litter size at birth with weight at later ages

Estimates of -0.26 and -0.19 show a highly significant negative association between litter size at birth and individual pig weight at 56 days and 154 days, respectively.

Table 38. Correlation coefficients among the five performance traits.

	Litter Size at 56 Days	56-Day Weight	Litter Size at 154 Days	154-Day Weight
Litter Size at Birth	.662**	-.255**	.651**	-.192**
Litter Size at 56 Days		-.019	.984**	.091**
56-Day Weight			.066*	.682**
Litter Size at 154 Days				.111**

These estimates are in agreement with other reports taken on a wide variety of breeds and herds under different conditions. An interesting point in these particular data is that litter size at later ages is positively associated with individual pig weights.

Perhaps those pigs in large litters which have inherited genes that enable them to survive until weaning have also inherited genes that enable them to grow vigorously, and thus they overcome the early handicap of being members of large litters.

3. <u>Litter size at 56 days and 154 days with individual pig weight</u>

Even though negative in sign (-.019), the correlation between litter size at 56 days and 56-day weight is only very slightly different from zero. By the time the pigs reach

154 days of age the correlation between litter size at 56 days with 154-day weight has actually become significantly positive. This same relation holds between litter size at 154 days and 154-day weight. As mentioned in the previous paragraph, the crossbred pigs seem to inherit a general vigor for survival and growth, and those from large litters that survive until weaning are genetically equipped to outgrow pigs from smaller litters, where the individuals have not been required to withstand as much competition in surviving from birth to weaning. The correlation between litter size at 154 days with 56-day weight has little biological meaning, because litter size at 154 days could hardly be a function of 56-day weight. However, the fact that it is positive, and significantly so, at least serves as verification of the other positive correlations between litter size and average weight.

4. Weight at 56 and 154 days

The positive correlation of .682 between these two traits is highly significant, as would be expected. It merely demonstrates numerically that the heavier pigs at 56 days are usually the heavier pigs at 154 days.

V. SUMMARY AND CONCLUSIONS

The data studied here were 1360 litters of purebred and crossbred pigs raised on two experimental farms over eight seasons. Although an effort was made to employ similar management and feeding practices on the two farms, productive characteristics such as litter size at birth, 56 and 154 days, and weight at 56 and 154 days differed markedly on the two farms. Litter size was consistently greater at the Ankeny farm, while growth rate was superior at the Napier farm. Seasonal influence also had marked effects, although some of the variation due to this source could be attributed to a linear increase in both litter size and weight.

Age of dam was also an important source of variation, 154-day old litters of gilts being 0.7 pigs smaller than those of yearling and older sows. Age of dam also had a significant effect upon pig weight at 56 and 154 days.

Nine inbred lines of Poland boars when "topcrossed" on Landrace sows yielded significant differences between the lines for 154-day weight and litter size at birth. Although the number of litters involved was small (83), and the disproportionality was extreme, the results of these topcrosses ranked the lines in approximately the same order of merit as earlier test matings on sows of Poland breeding.

Reciprocal crosses of Landrace and Poland breeds showed that crossing Landrace boars on Poland sows gave results much inferior to crossing Poland boars on Landrace sows. The cross-bred Landrace-Poland pigs were significantly superior in growth rate to pigs of the two pure breeds.

Duroc and Chester White boars were crossed on comparable samples of Poland-Landrace and Landrace-Poland sows to produce 466 litters. This system allowed three interesting comparisons: (1) between Duroc and Chester White boars, (2) between L x P and P x L sows, and (3) interaction of breed of boar with type of sow. The Chester White boars sired litters that were on the average one-half pig larger at birth but one-fourth pig smaller at 56 and 154 days than those sired by Duroc boars. Litters by Duroc boars were also heavier in average weight per pig at both 56 and 154 days. Comparison of L x P and P x L sows failed to demonstrate any evidence of maternal effect due to the way in which the two breeds were originally crossed. Interaction of breed of boar with type of sow was not significant, thus allowing a more general interpretation of the differences between the main effects.

Boars from four Beltsville strains, the Yorkshire and Hampshire breeds were crossed to comparable samples of Duroc-Poland-Landrace sows to produce 136 litters. There was doubt as to the statistical significance of differences between the boars, but the Hampshire and Yorkshire breeds did rank above the Beltsville strains in the final amount of marketable product.

Second cross sows of Duroc-Poland-Landrace breeding were either backcrossed to Poland and Landrace boars or further crossed to purebred boars of four other breeds. This project was represented by usable data from 246 litters. There was some evidence that use of a fourth breed gave superior results to the use of one of the two breeds originally used to start the cross. However, the poorest results in total litter production resulted when the Chester White was used as the fourth breed. A final conclusion on this problem must await the accumulation and examination of a great deal of additional data.

Seven breeds of boars and five breeding types of sows were involved in a study to compare litters from purebred and crossbred sows. Crossbred sows were superior to purebred sows in litter size at all ages. Landrace-Poland sows were superior to other combinations of crossbreds involving later generations of crossbreeding with Duroc, Chester White and Hampshire breeding.

It appears possible to attain high production and to maintain it through subsequent generations by a system of rotational crossbreeding using several breeds of boars upon succeeding generations of crossbred sows. There were definite advantages in using the Landrace in the early stages of the crossbreeding system because of the high production of crossbred Landrace sows. Initiating the system with Landrace sows and Poland boars was superior to reversing the sexes with the same breeds.

Correlation coefficients among the five performance traits measured were computed, using all 1360 litters involved in the study. As would be expected, correlation coefficients between the three measures of litter size were all large, positive, and highly significant. The correlations of litter size at birth with 56 and 154-day weights were negative and highly significant, but the situation was reversed at later ages. There was no correlation between litter size at 56 days and 56-day weight, but a highly significant positive correlation existed between litter size at 56 days and 154-day weight. A highly significant positive correlation of .682 between 56-day weight and 154-day weight served to demonstrate numerically that the heavier pigs at 56 days were usually the heavier pigs at 154 days.

VI. LITERATURE CITED

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